Final Report

A FAST-NEUTRON SPECTROMETER OF ADVANCED DESIGN

National Aeronautics and Space Administration

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A FAST-NEUTRON SPECTROMETER OF ADVANCED DESIGN

3 May 1965 to 3 February 1966

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FOREWORD

This is the final report on IITRI Project No. A6135, entitled "A Fast-Neutron Spectrometer of Advanced Design" and covering the period 3 May 1965 to 3 February 1966. The work was performed under National Aeronautics and Space Administration Contract No. NAS8-11885. The principal contributors to the research were Christopher C. Preston and Robert B. Moler. The data are recorded in Logbooks C16060 and C16437.

Respectfully submitted,

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ABSTRACT

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A prototype fast-neutron spectrometer based on a unique combination of solid-state detectors and He^3-filled proportional counters was developed. The instrument demonstrated a resolution of better than 100 keV and an efficiency of 2×10^{-6}/neutron over the energy range of 0.3 to 3 MeV. Gamma rejection of a high order was demonstrated.

The basic system consists of two silicon solid-state detectors separated by two proportional counters. Coincidence between the proportional counters is required. Particle identification is employed to improve gamma rejection and reduce other sources of background.

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A FAST-NEUTRON SPECTROMETER OF ADVANCED DESIGN

I. INTRODUCTION

The primary purpose of the research effort was to advance the state of the art of neutron spectrometry through the design, construction, and testing of a device utilizing a unique concept for the measurement of neutron spectra.

The ultimate purpose of this effort is to design and develop a fast-neutron spectrometer capable of recording high-resolution spectra of the neutrons leaking through a liquid hydrogen tank on board a nuclear rocket propulsion vehicle. Such a spectrometer must make accurate measurements within the following desired specifications: fast-neutron fluxes of $10^8/cm^2$-sec to $10^{10}/cm^2$-sec, a gamma field as high as 1.5×10^6 R/hour, and a time limit of 5 sec.

As a secondary benefit, this versatile instrument will be useful for a wide variety of neutron spectral measurements requiring a combination of good resolution, high efficiency, and rapid response. The need for such an instrument is demonstrated by the multiplicity of instruments that have been applied to the problem of measuring fast-neutron spectra. The problem is compounded for measurement of neutron spectra from extended sources, which require an isotropically responding neutron detector.

The solution to these measurement problems is embodied in an instrument that makes use of a unique combination of He^3-filled proportional counters and silicon solid-state detectors to achieve the combined properties of good resolution, high efficiency, rapid response, and effective gamma-ray rejection.

In the following sections general principles of neutron spectrometry are discussed, and the advantages and disadvantages of some widely used instruments are described. The combination system that was developed is described in detail, and the experimental results are compared with the expected results based on knowledge of the system parameters.

II. THEORY

A. State of the Art of Fast-Neutron Spectrometry

1. Introduction

Measurement of the spectra of fast neutrons (>0.1 MeV) has been a difficult problem in low-energy nuclear physics. Attempts to solve this problem have resulted in a large variety of approaches with varying success, as can be verified by consulting Marion and Fowler's volumes (ref. 1) on fast-neutron physics. Some of the more useful and widely used devices are based on proton recoil, measurement of neutron velocity by time-of-flight, and detection of products of neutron reactions with light elements.

a. Proton-Recoil Spectrometers

Scattering of fast neutrons by protons has been investigated extensively (ref. 1), and differential-scattering cross sections are known to be isotropic in the center-of-mass coordinate system up to about 5 MeV. Beyond this energy the results are less well known but can still be used for measurement of neutron spectra.

Use of proton-recoil measurement has the advantage that when small-angle scattering only is recorded the neutron spectrum is obtained directly from the recorded spectrum. In order for the small-angle scattering to be well-defined it is necessary that the neutrons form a collimated beam. A second advantage is that the scattering cross section is nearly constant to 15 MeV and is large (>15 barns).

A device that makes use of the above ideas is the proton-recoil telescope. In this instrument a thin polyethylene or other hydrogenous foil is interposed between a neutron beam and a proton detector. Additional detectors can be used between the foil and the proton detector to reduce background by means of a coincidence requirement.

The area of the foil and the detector, their separation distance, and the angular spread in the neutron beam define a geometric resolution; whereas the thickness of the foil places a lower limit on neutron energies that can be measured and also contributes somewhat to the resolution loss as a result of proton energy loss in the foil. To achieve reasonable resolution the foil must be very thin (<0.5 mg/cm^2), and consequently efficiency is low. Also, the efficiency requirements impose a limitation on low-energy response.

A variation that gives somewhat better efficiency, but at the expense of resolution and the low-energy limit, is the Rubbino spectrometer (refs. 2 and 3). In this device the scattering foil is in the shape of a barrel with a plastic-lead shield at the center to reduce the proton detector background that results from the direct neutron beam. This device is not useful below about 2.5 MeV.

Practical recoil spectrometers have been designed by Johnson and Trail (ref. 4) and others. The instrument of Johnson and Trail has a low-energy limit of 2 MeV and a resolution of 500 keV combined with an efficiency of 3×10^{-6}. Other designers have combined higher efficiency with poorer resolution and higher energy cutoff, or better resolution and lower energy with much lower efficiency.

A second general method of spectrometry based on n,p scattering records the spectrum of scattered protons and unfolds from this spectrum the neutron spectrum. This procedure requires very good statistical information if the unfolding procedure is to be reliable. When a hydrogen-filled proportional counter is used, spectral measurement of neutrons as low as 10 keV is possible with good resolution (3 to 5 keV full-width at half maximum). The efficiency of this method is high since a large volume of gas (ref. 5) or a large hydrogenous scintillator can be used. In a proportional counter large wall and end effects limit the energy range to less than 0.5 MeV. In a hydrogenous scintillator resolution is quite poor and gamma background is a serious problem. However, the gamma background can be partially corrected by pulse-shape discrimination.

b. Time-of-Flight Methods

One of the earliest neutron spectrometer techniques is based on time-of-flight. For keV and lower energies, the use of mechanical choppers gives good resolution and efficiency. At higher energies, other means of producing a neutron pulse are required. In Crockraft-Walton and Van de Graaff machines various beam-pulsing methods are employed, and the use of fast organic scintillators holds timing inaccuracies to less than 10^{-9} sec.

The resolution and the efficiency of time-of-flight methods are dependent on the length of the flight path, the time width of the initial burst, and the length of the neutron-detecting scintillator. A time-of-flight spectrometer with a resolution of 3 percent at 0.5 MeV and 15 percent at 14 MeV has been reported (ref. 6). The efficiency is constant at 10^{-7}/neutron, if the fact that the beam is pulsed at a 1 percent duty cycle to eliminate any overlap between pulses is discounted. Increasing the flight path to achieve better high-energy resolution sharply decreases the efficiency.

c. Neutron Reactions in Light Elements

There are a number of light element reactions that can be employed to detect fast neutrons. These include the $Li^6(n,\alpha)T$, $B^{10}(n,\alpha)Li^7$, and $He^3(n,p)T$ reactions.

The $Li^6(n,\alpha)T$ reaction has been used in the form of a lithium iodide (Eu) scintillator, but the resolution achievable is very poor and gamma interactions in the scintillator are a serious problem. The $Li^6(n,\alpha)T$ reaction has also been used in a solid-state sandwich detector. Resolution is good (150 keV full-width at half maximum), but the energy range is restricted because of the onset of competing reactions.

The boron trifluoride proportional counter is a classical neutron detector but gives very little energy information. The limitations in energy range, efficiency, or resolution of detectors using either the $Li^6(n,\alpha)T$ or the $B^{10}(n,\alpha)Li^7$ reaction are so severe that no further discussion is warranted.

The $He^3(n,p)T$ reaction is a very useful one, for several reasons. The reaction products, a proton and triton, share the neutron energy plus an additional 760 keV, the Q-value of the reaction. Thus the reaction of a thermal neutron with He^3 results in a peak at 760 keV if the energy of both the proton and triton is collected. This Q-value energy is advantageous since it provides a built-in calibration point and ensures that the neutron energy is well above the energy of many background sources. On the other hand, the Q-value energy is low enough that multichannel analyzers having a thousand or more channels or stable biased amplifiers are not necessary to provide a small enough energy channel width to distinguish among neutron energies of 200 keV and less. Of considerable importance also is the fact that the cross section of the $He^3(n,p)T$ reaction is high compared with other possible light element reactions and has no resonance structure to complicate analysis. This reaction has been utilized in a number of devices, among which the most important are the He^3-filled proportional counter and the solid-state sandwich detector.

The earliest He^3-filled proportional counters, those of Bloom and Batchelor (ref. 7), were limited to neutron energies below about 2 MeV because of the onset of interference from the $He^3(n,n)He^3$ scattering reaction and the difficulty of making corrections for this effect. Additionally, the contamination of He^3 with H^3 is troublesome, since it results in degradation of resolution. These instruments can give a resolution of 10 percent at 1 MeV and an efficiency of 10^{-4}/neutron.

A recent development of He^3-filled proportional counters is Sayres' use of pulse-shape discrimination for gamma- and helium-recoil rejection (ref. 8). This device is useful up to 10 MeV but has the disadvantage that the pulse rise time discrimination method does not operate over the full energy range for a given setting used to achieve optimum neutron detection. The instrument has a constant resolution of approximately 100 keV and an efficiency of 10^{-4}/neutron. Another advantage is that knowledge of the neutron direction is unnecessary.

The use of He^3 as a converter with the product particles being detected by two solid-state detectors was pioneered by Dearnaley (ref. 9). In this detector the sum of the energy of pulses in coincidence is recorded. The coincidence requirement eliminates background from He^3 recoils and H^3 decays as well as reduces the sensitivity to gamma interactions. The resolution is 150 keV and the efficiency is 10^{-5}/neutron. The most serious difficulties are the large $Si^{28}(n,p)Al^{28}$ and $Si^{28}(n,\alpha)Mg^{25}$ cross sections at neutron energies above 6 MeV and the large gamma sensitivity.

In the spectrometer design developed here, the features of the He^3-filled proportional counter and the solid-state sandwich detector have been combined to take advantage of their useful properties and to partially eliminate their drawbacks.

2. Summary

The above techniques and instruments for fast-neutron spectrometry all have been used to make measurements of fast-neutron spectra in a variety of applications. Each instrument has advantages that make it particularly useful in some applications but disadvantages that make it inapplicable for other situations. The most frequent disadvantages are lack of resolution, limited energy range, high background, or some combination of these three. Each type of spectrometer has been applied to a specific type of measurement and has been limited to that type of measurement.

The recoil telescope requires extensive shielding to eliminate the large background generated by scattered neutrons and cannot make spectral measurements in an environment where the neutron source is other than a point or is a collimated beam, such as from a reactor port.

Time-of-flight techniques have their greatest utility in measurement of angular distribution of neutrons from (X,n) reactions in which the source can be pulsed at the appropriate high speed required. The recoil telescope and spectrometers based on light element reactions cannot generally compete in this application, and it is equally clear that time-of-flight techniques are not applicable for spectral measurements of an extended source operating continuously.

The detection of the reaction products of light element reactions with neutrons has the special advantages of being indifferent to the neutron direction and of responding continuously. The major disadvantage of this technique is the high background that may be encountered, although this problem has been reduced by applying coincidence techniques and pulse-shape discrimination.

The following section describes a neutron spectrometer that employs the $He^3(n,p)T$ reaction and has inherently good resolution and low background. Since it is one of the class of spectrometers that utilizes the detection of the products of light element reactions with neutrons, it has the desirable property of isotropic and continuous response.

B. Combined H^3-Filled Proportional Counter and Sandwich Spectrometer

1. Description

The use of the $He^3(n,p)T$ reaction as a neutron converter has several advantages. If the total energy of the secondary particles, the proton and triton, is absorbed, the spectrum recorded is easily interpreted. Since this reaction has a Q-value of 0.760 MeV, the energy from a recorded neutron is well above most background. A resolution of 30 to 50 keV can be achieved. Neutrons whose absolute energies are 2 to 3 times this value, that is, neutrons with energies as low as 100 keV, produce peaks that can be resolved from the peak resulting from thermal neutrons. The cross section of this reaction from 50 keV to 15 MeV is shown in Figure 1 (ref. 10).

In the simple solid-state sandwich spectrometer the products of the reaction of neutrons with He^3 atoms are recorded in coincidence by two solid-state charged-particle detectors. The coincidence requirement eliminates He^3 recoils from the spectrum but does not eliminate the spurious events due to the $He^3(n,d)D$ reaction. In a He^3-filled proportional counter pulse-shape discrimination has been used to eliminate gamma interaction from the spectrum and to partially eliminate spurious response from the $He^3(n,d)D$ reaction.

Theoretical considerations indicate that a number of advantages can be realized if a method that makes use of the volume of He^3 gas present in the solid-state sandwich spectrometer can be developed. The simplest arrangement is to use the He^3 gas as a proportional counter. Somewhat better resolution will be achieved by adding the energy deposited in the proportional counter to that absorbed in the solid-state charged-particle detectors. Much lower background will be achieved by

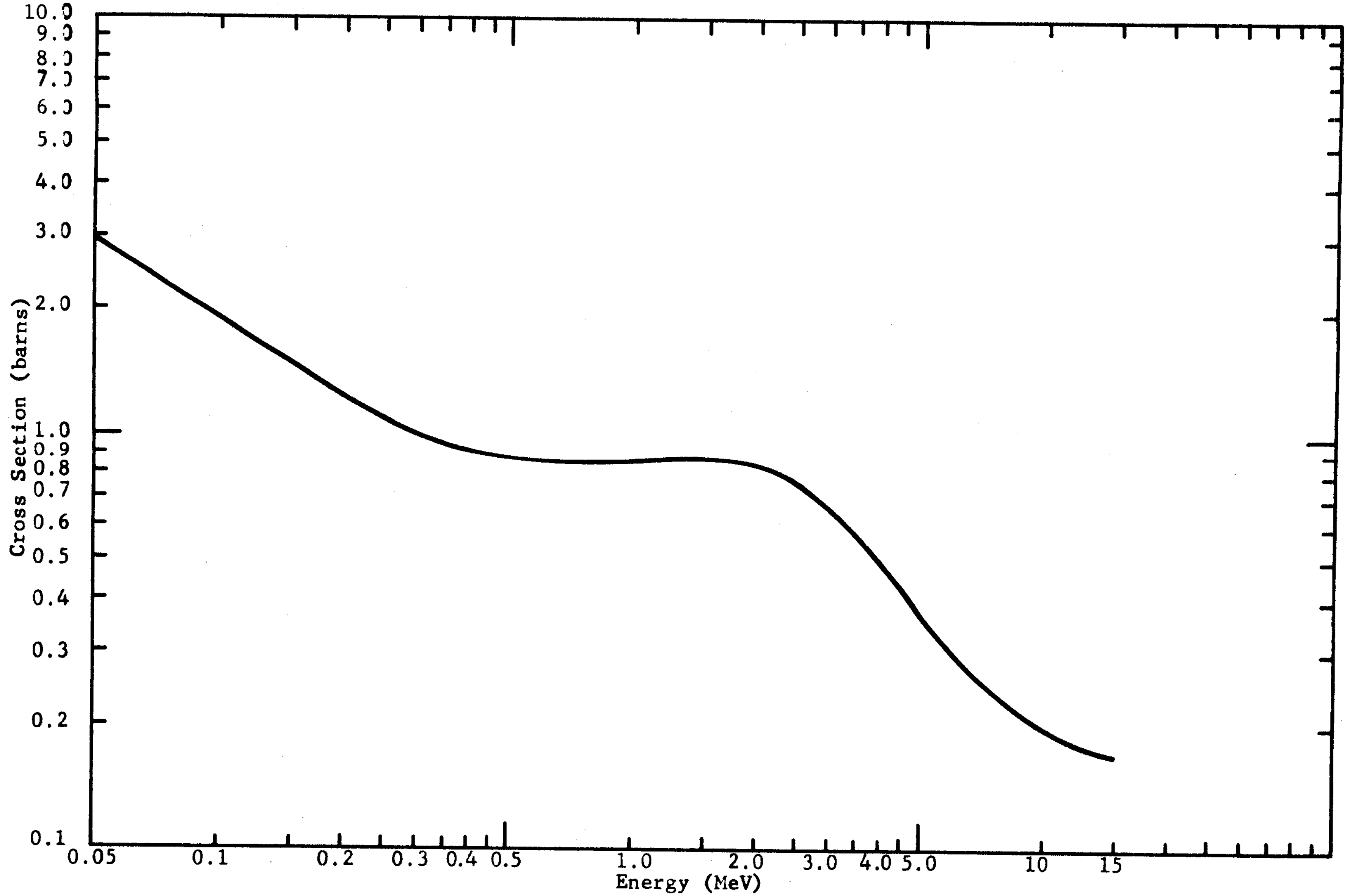


Figure 1

CROSS SECTION OF THE $He^3(n,p)t$ REACTION FROM 50 keV TO 15 MeV requiring coincidence between the solid-state detector and the porportional counter.

An extension of the above use of He^3 gas as a proportional counter is to divide the volume into two proportional counters. Such an arrangement presents the possibility of using particle identification techniques to eliminate gamma interactions, He^3 recoils, deuterons from the $He^3(n,d)D$ reaction, alpha particles from the $Si^{28}(n,\alpha)Mg^{25}$ reaction, and many of the protons from the $Si^{28}(n,p)Al^{28}$ reaction.

The above ideas were incorporated into a neutron spectrometer in which the gas volume is divided into two proportional counters separated by a series of wires to define the electric field. Coincidence between the two proportional counters is required. A further requirement is that a proton be identified through its (dE/dX)xE product.

It is instructive to estimate the resolution, efficiency, and background to be expected from this basic system.

2. Resolution

Available surface-barrier solid-state detectors have proton resolutions as low as 20 keV. The two simple proportional counters can be designed with resolutions of 5 percent at 100 keV and 20 percent at 10 keV. At low neutron energies the two proportional counters might be expected to share 100 keV of energy between them. If the sharing is equal, the resolution in each counter will be 3 keV. The electronic contribution in each of the four channels will be of the order of 5 keV for available amplifiers. Summing these contributions in quadrature yields a figure of 32 keV. Somewhat better solid-state detectors are occasionally available, so that a resolution of 25 keV might be achieved.

3. Efficiency

The efficiency depends on the size and the spacing of the solid-state detectors and on the gas pressure. For spacings other than essentially zero, the efficiency is energy dependent and is significantly so at neutron energies of 5 Mev and higher (ref. 11).

For a gas pressure of 2 atmospheres and a volume of 1 cm^3, an efficiency of 10^{-5}/neutron can be achieved for energies up to 3 MeV, the cross section being relatively constant from 0.3 to 3 MeV. Above 3 MeV the cross section has an approximate 1/V dependence to beyond 14 MeV.

4. Background

The background that can be expected is that from gamma interaction in the gas and solid-state detectors and from neutron interaction in the solid-state detectors.

For gamma interaction in the gas, the mass attenuation coefficient is approximately 0.1 cm^2/g at a photon energy of 50 keV and decreases at 0.02 cm^2/g at 100 keV and higher energies (ref. 12). This implies that the efficiency for detecting gamma rays in the gas is $<2 \times 10^{-5}$/photon. The electron that results from this interaction has a large range.

For example, for a 50-keV electron the energy loss will be less than 1 keV per centimeter in helium at 1 atmosphere, and the energy deposited in the gas by a gamma interaction will rarely be greater than 5 keV. This is much smaller than the energy deposited by a proton or triton, so that gamma interaction events can be eliminated from the proportional counter channel on the basis of energy discrimination alone. In addition to the energy discrimination, the requirement of coincidence between the proportional counters reduces the number of recorded gamma events by a large factor. A final method of discrimination makes use of the particle identification technique, which will be very effective for distinguishing between electrons and protons. Energy discrimination, proportional counter coincidence, and the particle identification technique are all used.

Gamma interaction in the solid-state detector channels may result in many pulses, which will pile up in a charge-sensitive preamplifier. This difficulty can be eliminated by fast gating into the charge-sensitive preamplifier only those pulses in coincidence with the proportional counters. These pileup effects and their elimination are discussed in detail in Section IVE.

Neutron interaction in the silicon of the solid-state detector is a somewhat more difficult problem. The $Si^{28}(n,\alpha)Mg^{25}$ reaction has a threshold of approximately 5 MeV; the cross section is 300 millibarns at 8 MeV and decreases to 35 millibarns at 14 MeV (ref. 13). The $Si^{28}(n,p)Al^{28}$ reaction has a threshold of approximately 4 MeV; the cross section is 500 millibarns at a neutron energy of 8 MeV and decreases to 250 millibarns at 14 MeV (ref. 14).

In the $Si^{28}(n,\alpha)Mg^{25}$ reaction the alpha particle can be identified by its characteristic (dE/dX)xE product and thus eliminated. In the $Si^{28}(n,p)Al^{28}$ reaction elimination of the proton is not possible. Since these protons are emitted isotropically from the silicon, the geometry causes some attenuation. Some of the time both (dE/dX)xE discriminators will identify a proton, and this is not allowed by the logic circuit. It is expected that these two effects will reduce the background from this source to a level that is tolerable. The main background contribution from the $Si^{28}(n,p)Al^{28}$ reaction resulting from 14-MeV neutrons will occur at energies below 5 MeV. Since for most neutron spectra of interest the number of neutrons at 14 MeV is small compared with the number below 5 MeV, the interference from this background source will be negligible. In those cases in which high-energy monoenergetic neutrons are expected, a background measurement taken with He^4 in the counter may be required.

Another source of background is that from the $He^3(n,d)D$ reaction. The background from this reaction is eliminated by the particle identification circuit, which demands a proton before an event can be recorded.

Other possible sources of background are interaction of neutrons and gamma rays in the chamber walls and wires and interaction of charged particles from outside the chamber with the walls or detectors. The probability of the latter is negligible because of the coincidence and the particle identification requirements. For the same reason, background from neutron interaction in the chamber walls is negligible. Gamma interaction in the walls may contribute to the gamma background because the high-energy electrons being ejected from the walls may give rise to a secondary emission of electrons having enough total energy to trigger the coincidence circuit.

III. APPARATUS

A. Detector Chamber

1. Construction

The detector chamber is shown in Plate I, and detailed drawings are shown in Figures 2 and 3. The chamber consists of two silicon surface-barrier detectors of 16-mm diameter separated by 5 cm. This volume is divided by a series of seven 0.004-in.-diameter stainless steel wires, which form a virtual wall that electrically separates the two volumes. These wires are at chamber potential. Two wires 0.002 in. in diameter, one in each volume and insulated from the chamber, are the anodes of each proportional counter. Small glass-to-metal seals (type 105-HT, The Fusite Corp.) are used at one end of the wire, while miniature hermetic coaxial connectors (type TISM, Physical Sciences Corp.) are used at the opposite end. The solid-state

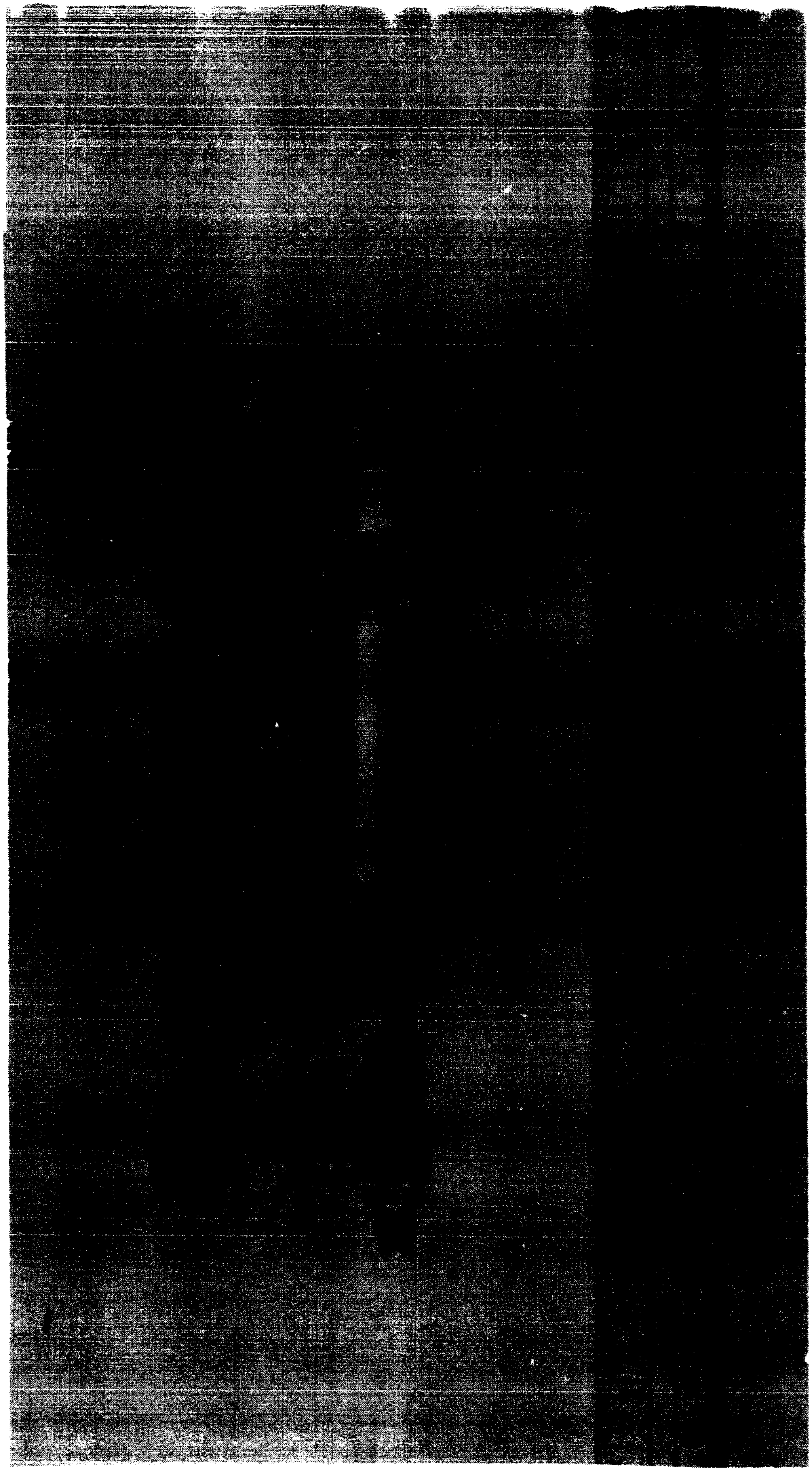
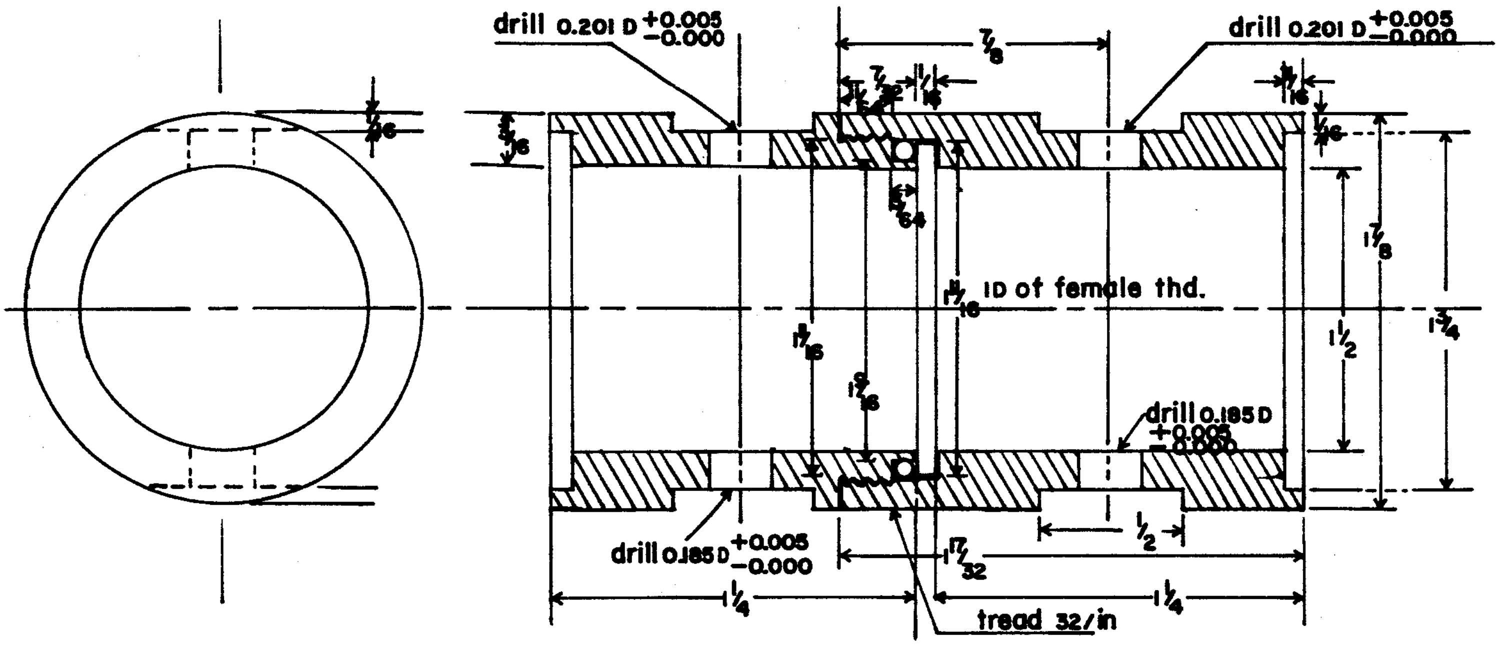


PLATE I

PHOTOGRAPH OF THE NEUTRON DETECTOR CHAMBER



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All dimensions ±0.005
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Figure 2

DRAWING OF THE CHAMBER BODY

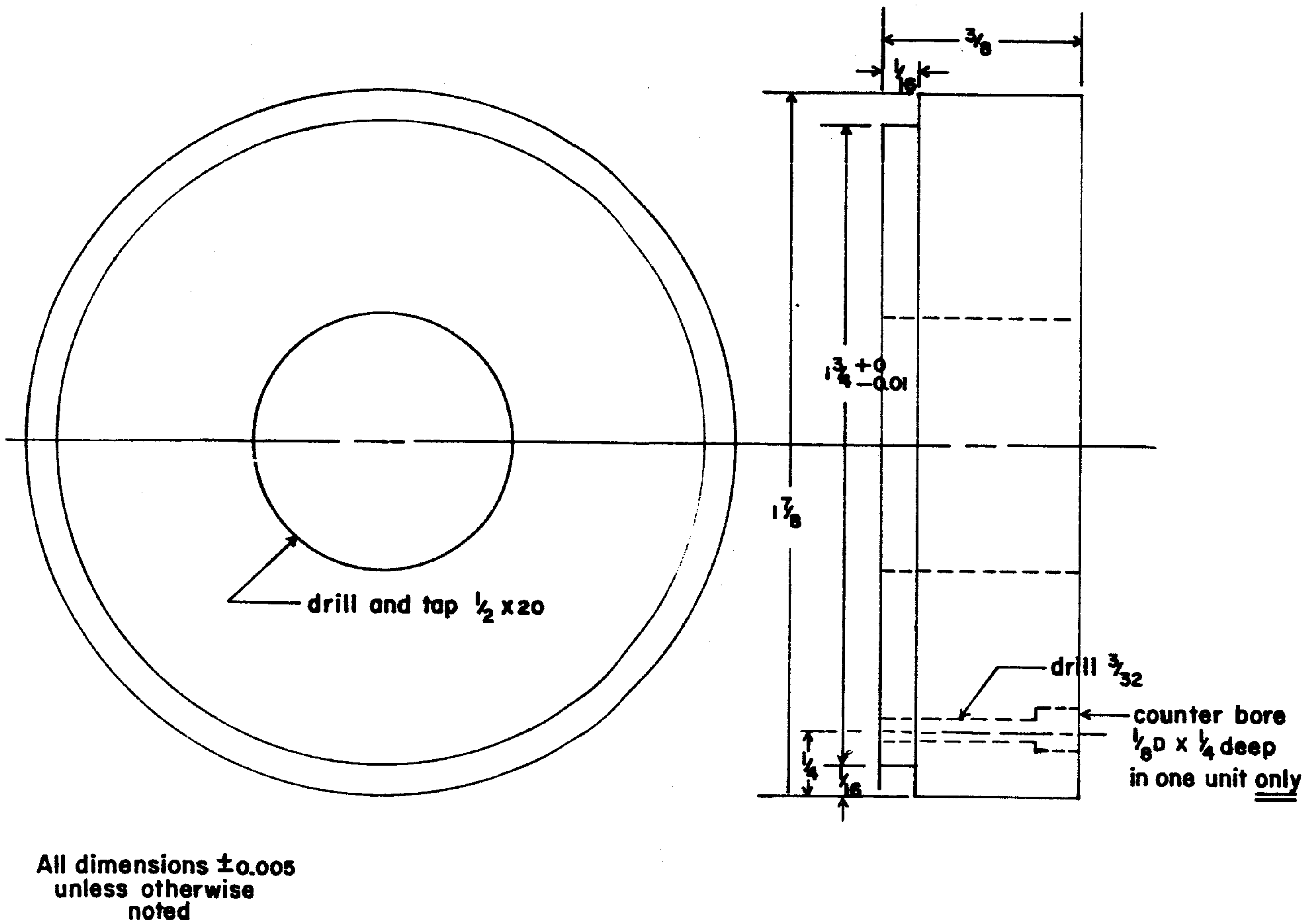

Figure 3

DRAWING OF THE END PIECE OF THE CHAMBER

detectors are mounted in the ends of the chamber with a hermetic coaxial feedthrough connector (type C-14, Oak Ridge Technical Enterprises).

2. Proportional Counter Operation

The area of the series of wires that separate the two proportional counter volumes is small compared with the total area, and therefore the probability of stopping a proton that passes through this area is negligible.

The electrical field around each anode wire is quite non-uniform because of the shape of the chamber. This results in a variation of gas multiplication along the length of the wire (ref. 15). Most events of interest will occur near the center of the volume, where this variation is least important. The fact that gas multiplication is low (<10) also minimizes variation. Finally, the actual energy deposited in the gas is small compared with that deposited in the solid-state detectors, so that the variation in pulse height from the proportional counters has a small effect on the full-width at half-maximum of the sum peak.

Gas pressures from 0.25 to 2.0 atmospheres can be used. For the lowest pressures, potentials of 500 to 600 volts are expected for a gas multiplication of 10 in a mixture of 90 percent He^3 and 10 percent C_4H_{10} (isobutane). At 2 atmospheres the voltage required increases to about 1000 volts.

Since these counters are to be used to derive a fast-coincidence pulse, it is important to know whether the timing accuracy will be adequate to achieve high coincidence efficiency at resolving times (2τ) of less than 100 nanosec and possibly as low as 10 nanosec. The electron drift times in the 90 percent He^3-10 percent C_4H_{10} mixture at a voltage gradient of 250 volts/cm and a pressure of 0.25 atmosphere is approximately 3×10^6 cm/sec. This implies a pulse rise time of about 300 nanosec in the proportional counters. Timing accuracies of better than 50 nanosec should present no problem, an expectation that is indeed borne out in practice.

B. System Electronics

Figure 4 is a block diagram of the electronics. The four preamplifiers are Tennelec model TC-100Bs having 2.5-keV noise at zero input capacitance. The four main amplifiers are Tennelec TC-200s (Tennelec Instrument Co., Oak Ridge, Tenn.). The amplifiers are of the resistance-capacitance differentiating and integrating type and have time constants between 0.05 and 12 microsec. The crossover-pickoff units and the fast-coincidence units are Oak Ridge Technical Enterprises models 407 and 414, respectively. The fast coincidence is variable between 10 and 110 nanosec. The adders, shown in Figure 5, were designed and built at IIT Research Institute and are based on the circuit of Rogers (ref. 16). The major difference between this circuit and that of Rogers' is the modification to allow bipolar pulses to be added linearly.

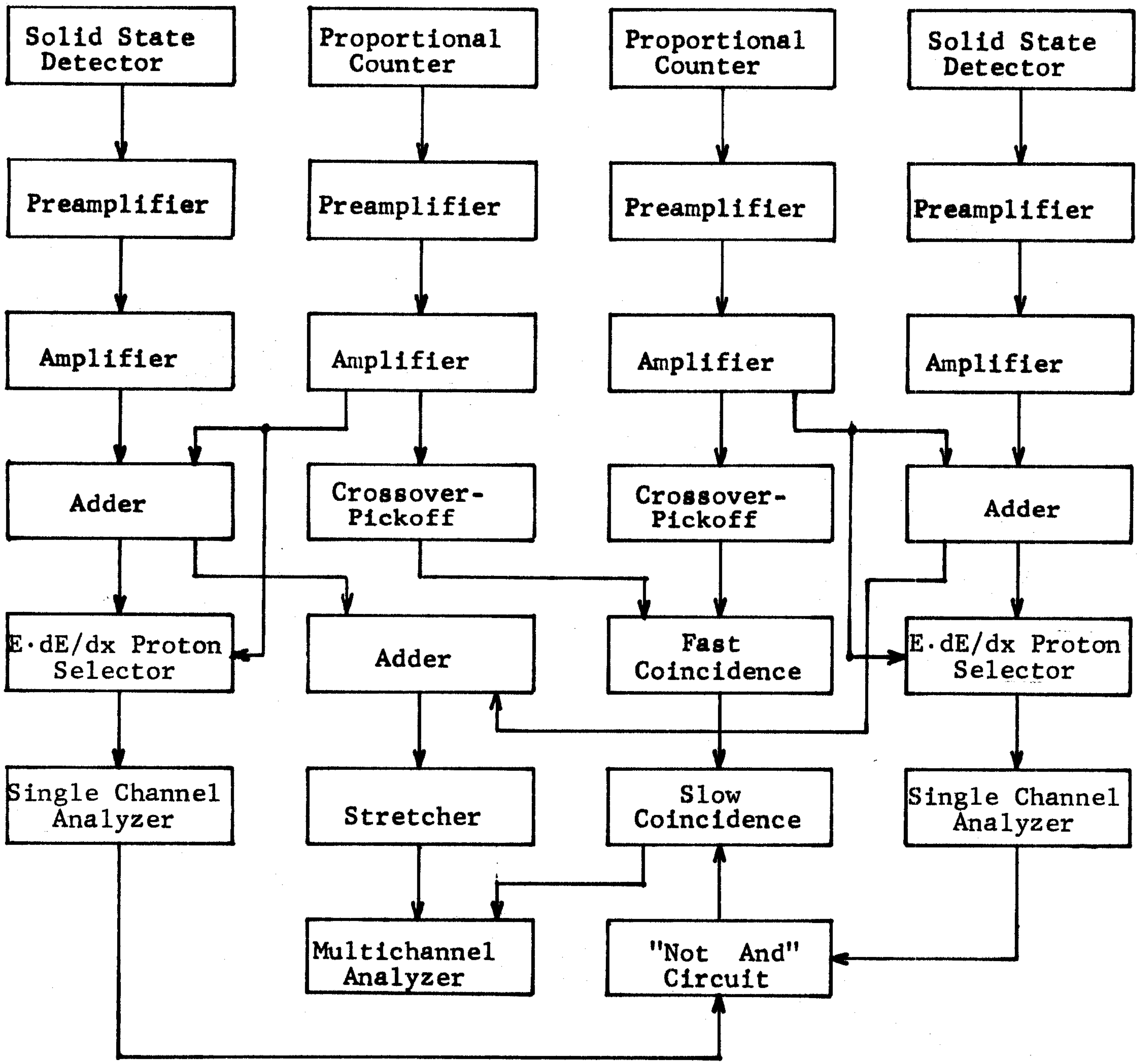

Figure 4
BLOCK DIAGRAM OF THE ELECTRONICS

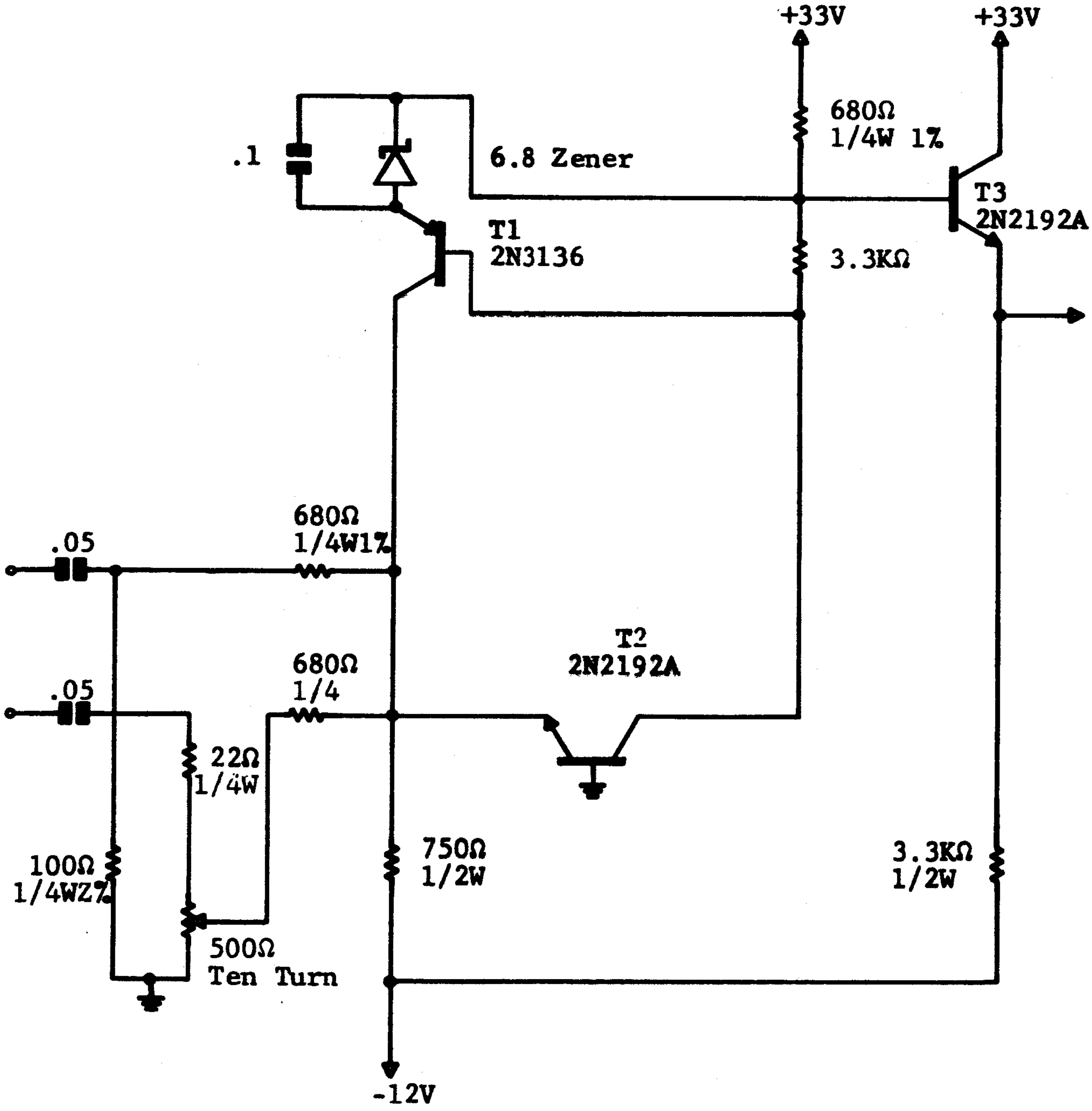

Figure 5
ADDER CIRCUIT

The multiplier circuit (ref. 17) is based on the Hall effect, in which the output voltage between two edges of a semiconductor wafer is given by

$$V_x = KIyB_z \quad , \tag{1}$$

where K is a constant characteristic of the material, I is the current across the device perpendicular to the output voltage, and B is the magnetic field perpendicular to both the current and the voltage.

In general, it is difficult to produce a rapidly changing magnetic field in response to a current pulse. The magnetic field is proportional to a current I, which for the pulse of interest must have rise times of less than 1 microsec in order to handle high count rates. A practical Hall multiplier unit has an inductance of 50 μh and a maximum current of 2.5 amperes. The voltage necessary to drive a 50-μh inductance to 2.5 amperes in 0.5 sec is given by

$$E = L \frac{dI}{dt} \quad . \tag{2}$$

This results in a maximum voltage of 250 volts. A circuit with a standing current of 2.5 amperes at 250 volts would dissipate 625 watts, which is an impractical figure. Therefore a more reasonable approach was sought.

The circuit shown in Figure 6 minimizes dissipation by using transistors with a high (400-volt) collector-to-emitter breakdown voltage in a switching circuit. The inductances, L_1 and L_2, are much larger than the inductance of the Hall device

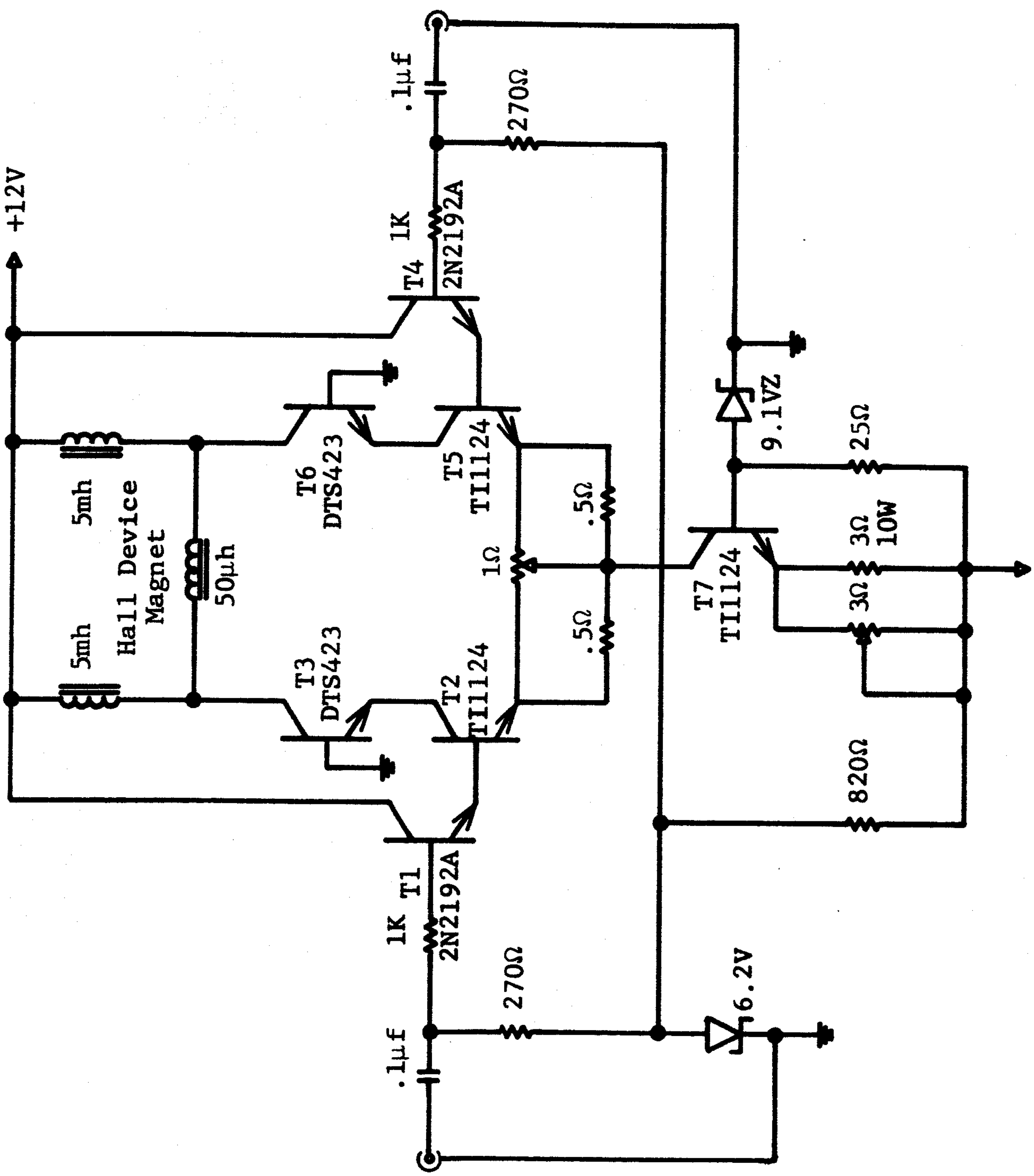

Figure 6
HALL MAGNETIC CIRCUIT DRIVER

and can supply the current to the Hall device as each transistor is turned off as a result of the negative part of a bipolar input pulse.

Another necessary circuit for the multiplier is the input current driver shown in Figure 7. This circuit produces a maximum current of 250 ma for an input of 10 volts.

The output of the Hall multiplier is 10 millivolts or less and must be amplified to a level that operates a single-channel analyzer. This amplification is done with the circuit of Figure 8.

Operation of the multiplier based on the Hall effect was disappointing. Input pulses of less than 2-microsec rise time caused instability and oscillations. Such oscillations frequently reached peak amplitudes exceeding the breakdown voltage of the switching transistors. When this occurred, transistor failure was immediate.

Because of these difficulties, which made operation unreliable, as well as the large power supply required, other means of performing the multiplication were sought. Of the methods investigated, multiplication based on the characteristics of the field-effect transistor appeared to be the most promising. An earlier investigation had indicated that field-effect multipliers were useful for low-frequency continuous sine waves but could not be readily adapted to the multiplication of fast pulses. The subsequent publication of several papers (ref. 18) describing pulse multipliers based on field-effect transistors

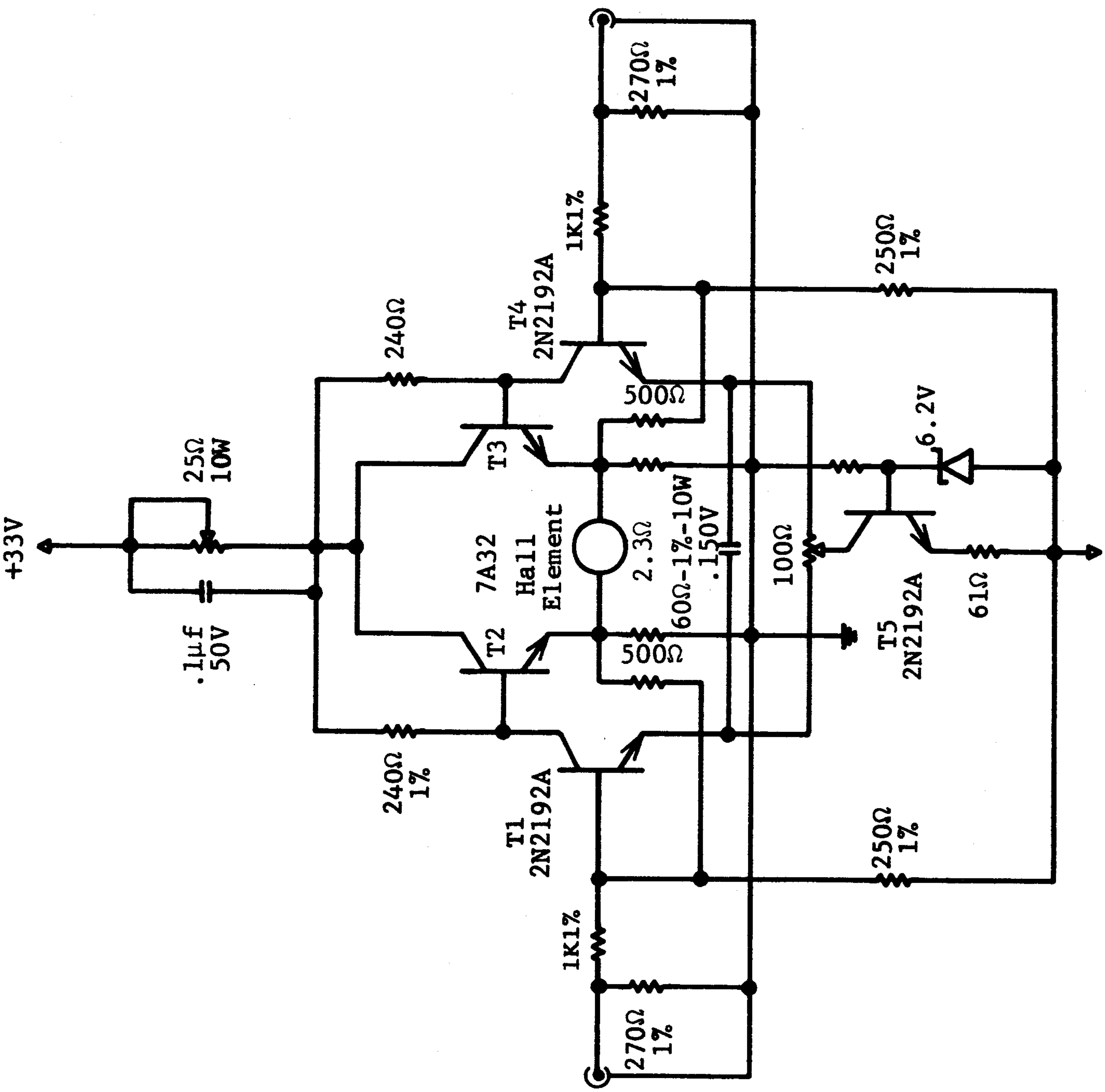

Figure 7
HALL INPUT CURRENT DRIVER

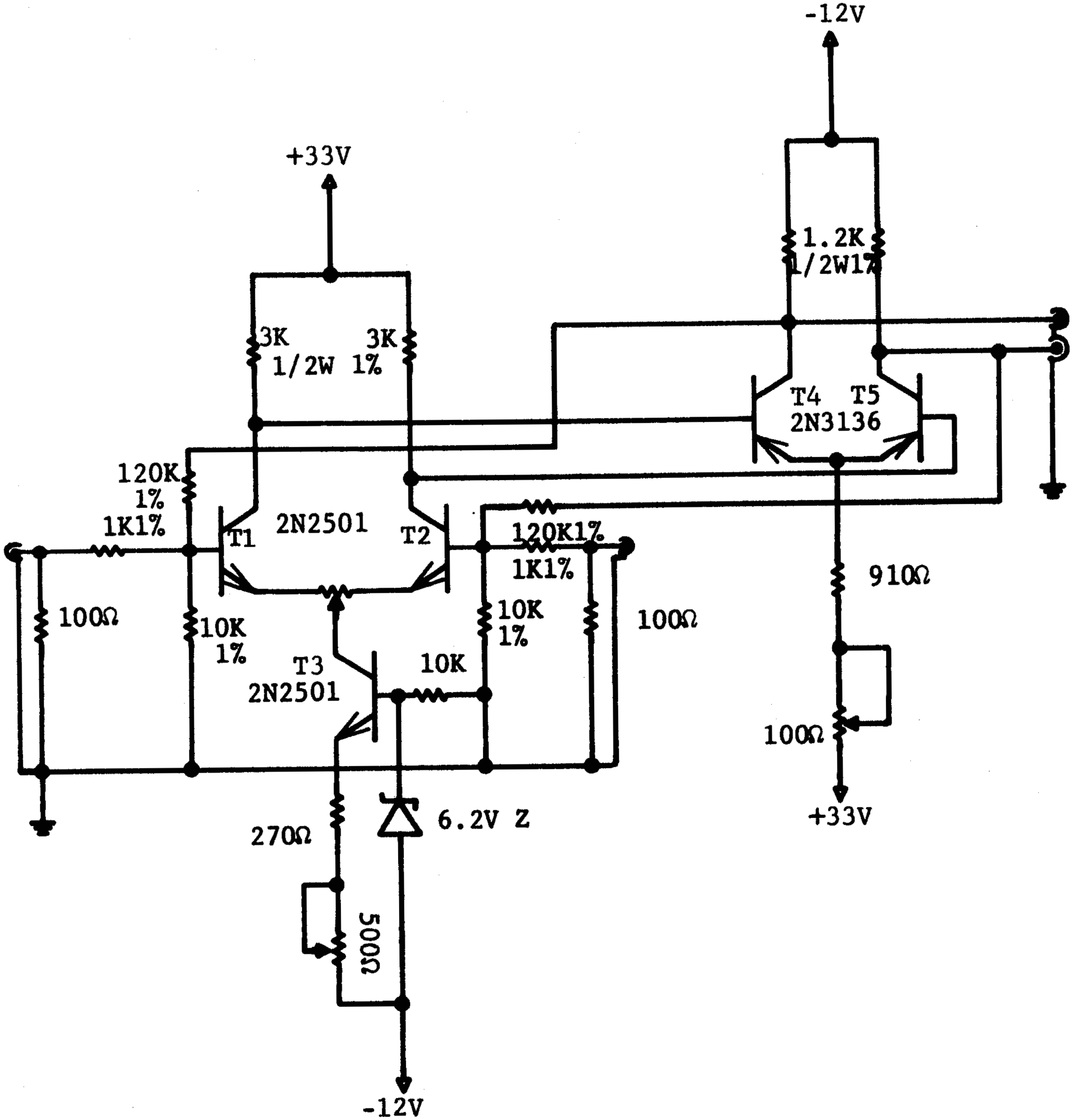

Figure 8

HALL OUTPUT AMPLIFIER

and the availability of high-frequency devices required reevaluation of this conclusion.

The circuit of Highlegman (ref. 19) was studied and a similar multiplier constructed. This multiplier circuit has the useful properties of low power drain and simplicity. Preliminary tests indicated that it is stable, reasonably linear, and probably reliable. Pulses with rise times as short as 0.2 microsec could be multiplied. Thus a multiplier of this general type is well suited for inclusion in the instrument package of the fast-neutron spectrometer, especially in view of its ultimate application as a flyable instrument.

The logic circuit that contains the "exclusive or" (not and) function and the slow coincidence is a simple half-adder of the integrated circuit variety together with a similar dual two-input gate. The half-adder performs the coincidence and inversion function, while the adder generates an anticoincidence pulse for the "exclusive or" function. The output of this circuit triggers a univibrator used to open the analyzer gate.

C. System Operation

The operation of the complete system and the logic requirements are as follows. A neutron interacts with a He^3 nucleus to produce triton and a proton. The two particles must deposit enough energy in the two proportional counters to trigger both crossover pickoff units. These two pulses are required to be related in time so that they trigger the fast-coincidence circuit. Either one but not both of the discriminators that signal the recognition of a proton must be triggered. The energy recorded in the four detectors is summed, and this pulse is presented to a multichannel analyzer for analysis if the previous logic requirements have been met.

IV. EXPERIMENTAL

A. Testing of System Components

Before the system was operated in a neutron environment, a number of tests were made to verify proper operation of the system.

1. Proportional Counter Tests

The proportional counters were initially filled to 0.5 atmosphere with He^4 mixed with various percentages of C_4H_{10}. Drift velocities are a function of both the gas mixture and the applied voltage, so that at a given pressure a gas mixture and a voltage can be chosen to produce minimum, constant drift times through the sensitive volume of the counter. For C_4H_{10} percentages of less than 1 percent, the drift time appeared uniform but resolution suffered because the range of the proportional region was contracted. As the amount of C_4H_{10} was increased to 10 percent, the proportional counters became stable and linear. These tests were made with a Po^{210} alpha source inside the counter.

The resolution of the proportional counter was measured at 0.25, 0.5, and 1.0 atmosphere of 90 percent He^4 and 10 percent C_4H_{10}. These measurements were made by operating a proportional counter and a solid-state detector in coincidence to ensure that only those alpha particles that passed through the central part of the proportional counter were recorded. These results indicated a resolution of 10 percent at 1 MeV and 0.25 atmosphere pressure. At the higher pressure of 1.0 atmosphere, the resolution increased to 20 percent. These resolution figures are principally determined by the nonuniform electric field gradient and the consequent nonconstant gas multiplication. These resolution figures are disappointing, but it is considered that a slight change in the geometry will minimize this effect and improve the resolution substantially.

2. Solid-State Detector Tests

The alpha resolution of both solid-state detectors was measured with the chambers evacuated. This resolution was found to be 48 keV for detector A and 38 keV for detector B. The noise due to the cable and other capacitances was found to be 25 keV. This result was measured by using a calibrated mercury relay pulser to deposit a known quantity of charge into the input of the preamplifier with the detectors connected to the preamplifiers and with bias applied.

The manufacturers' specification for the resolution of detector A is 41 keV and for detector B is 27 keV. These figures, when added quadracly to the system noise (25 keV), correspond closely to the measured resolutions.

If the noise widths of these detectors, 32 keV for detector A and 21 keV for detector B, are used as the effective proton resolution, the best possible resolution that can be expected for the spectrometer is 54 keV.

3. Coincidence Measurements

Coincidence efficiency was measured, again by using the pulses as a simulated signal source. For any resolving time between 10 and 100 nanosec the efficiency was 100 percent for pulses greater than 0.2 volt into the crossover pickoff units. This was true for any RC time constants between 0.2 and 4 microsec for the proportional counters and between 0.05 and 4 microsec for the solid-state detectors. No fixed delay was required to achieve 100 percent coincidence efficiency for any setting of the amplifier time constants. This indicates that charge collection time is closely matched in these counters for a given high voltage, in spite of their unusual geometry.

The poorer of the two solid-state detectors exhibited a rounded leading edge and slower rise time of the preamplifier pulse. This effect is attributed to carrier trapping, which reduces the carrier mobility. Because of this effect, a fixed delay of 100 nanosec was required between this detector and the other to achieve proper timing of coincidence pulses.

4. Drift of Electronics and Detectors

By monitoring the alpha peaks occurring in the two solid-state detectors it is possible to ascertain whether any significant drifts occur in the solid-state detectors or the electronics. Long-term studies of this effect before and after substantial, integrated gamma and neutron doses showed that detector B did not drift a measurable amount for any time up to 24 hours. On the other hand, detector A, the detector having the poorer resolution and the slower rise time, did drift a serious amount. In one instance the amount of drift was 4 percent over a 16-hour period. The amount of drift was greatest during the first few hours of operation after the detector bias voltage had been removed and reapplied. For several hours after the bias had been slowly reapplied, the detector and preamplifier exhibited high noise and instability, but as the system aged, this effect diminished. After 24 hours of operation at 200 volts, stable operation was usually again possible. Such behavior is not typical of surface-barrier detectors and is probably the result of the poor quality of this particular detector. Usually high-resolution detectors do not exhibit such effects although it is generally recommended that bias be applied slowly to any detector.

The above drift problem was not initially apparent to more than an insignificant extent but became progressively more pronounced after neutron irradiation. The worst case of drift occurred when the detector bias was removed and then restored after a neutron dose of approximately 10^{11} NVT accumulated during experiments extending over several weeks. Resolution in the detectors did not deteriorate after this dose.

B. Neutron Response to Isotopic Sources

The first attempt to record neutrons made use of a small PuBe isotopic source. This source has a yield of approximately 10^6/sec. With the 1-in. x 2-in. cylindrical neutron source parallel to the neutron detector, it is estimated that a maximum of 10^5 neutrons/sec passes through the sensitive gas volume of the detectors. Since even at the maximum credible neutron efficiency only 1 neutron/sec would be recorded, a spectrum could not be obtained in a reasonable time. As later results verified, the efficiency at the 0.5 atmosphere pressure used was only 10^{-6}/neutron, so that more than about 300 counts/hour distributed over some 200 channels could not be expected.

In the first run in which coincidence was required between the solid-state detectors, a low-energy tail was observed. It was attributed to gamma-ray interaction in the solid-state detectors. This assumption was verified by placing a 4-in.-thick lead shield around the detector. The response to gammas was sharply reduced. The residual background was attributable to the 4.43-MeV gamma rays resulting from the $Be^9(\alpha,n)C^{12*}$ reaction, which leads to the 4.43-MeV level in C^{12} (ref. 20). The shielding was not effective for this gamma energy.

Surrounding the source with 6 in. of paraffin to moderate the fast neutrons resulted in a thermal peak, although the efficiency was still quite low because of the increased separation required.

The use of the higher-yield IITRI ABC (americium-beryllium-curium) source proved to be advantageous. This source has a yield of approximately 10^7 neutrons/sec, although its fission-product gamma flux is much higher than the gamma flux from the PuBe source. This flux was measured as 30 mR/hour at 1 foot and approximately 1 R/hour at the surface. With a coincidence being required between the solid-state detectors, a gamma background of 300 counts/min was recorded. Use of the gamma shield previously constructed reduced the background to 30 counts/min, the residual resulting from the alpha source inside the chamber.

It was necessary that the complete setup of detector and source be surrounded by paraffin to reduce the radiation hazard in surrounding areas. The neutron spectrum from this source was thus considerably distorted by the large flux of partially thermalized neutrons. Figure 9 shows a spectrum of the ABC source recorded during a 72-hour run under these conditions. Little structure is discernible except for the broad peak at 4 to 5 MeV. This is the major peak observed in the spectrum of an americium-beryllium source (ref. 20), and the rising spectrum below 4 MeV is approximately that expected in this environment. An energy bias was used to eliminate the very large thermal peak that would have occurred at an energy of 760 keV. No measurable drift occurred during this interval, as was verified by noting that the alpha peaks from each solid-state detector still occurred at the same channel number.

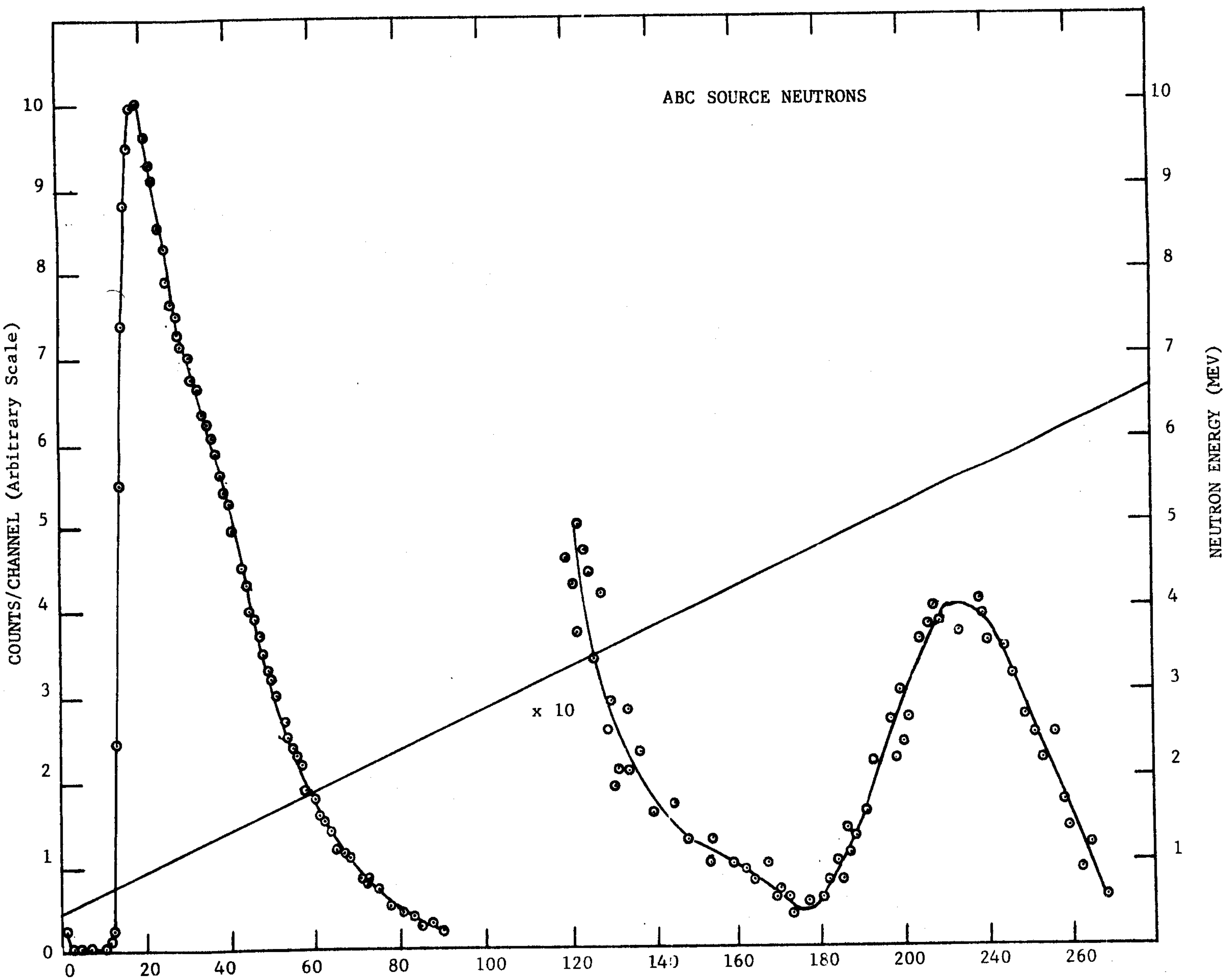

Figure 9
NEUTRON SPECTRUM OF ABC SOURCE IN SHIELD

Figure 10 shows the thermal peak resulting from moderated neutrons. Resolution information can be derived from this peak, although the width is broadened because of the large cross section of the $He^3(n,p)T$ reaction at energies up to 50 keV and the large neutron fluxes there. The half-width of this peak is 100 keV, which represents maximum resolution. If the energy spread of the neutrons contributing to this peak is ignored and only the energy spread due to the proportional counters is considered, a more realistic resolution can be calculated with some confidence. The energy spread due to the proportional counters at a pressure of 0.5 atmosphere is 75 $\pm$ 5 keV. This figure gives a resolution of 66 $^{+12}_{-6}$ keV.

In a second experiment carried out with the ABC neutron source coincidence information was taken from the proportional counters. The reduction in gamma background in this mode was striking. No gamma background was recorded in several hours with 90 percent He^4 and 10 percent C_4H_{10} in the detector to a pressure of 0.25 atmosphere. No shielding was required to record the neutron spectra.

An unshielded spectrum of the ABC source is shown in Figure 11. Background has been subtracted from this spectrum, and a typical background spectrum is shown in Figure 12. In the background spectrum the 5.3-MeV alpha peak of Po^{210} is the principal component. The small broad peak at 4 MeV is due to alpha scattering in the walls of the chamber. At the low pressures used in these experiments, adding the proportional

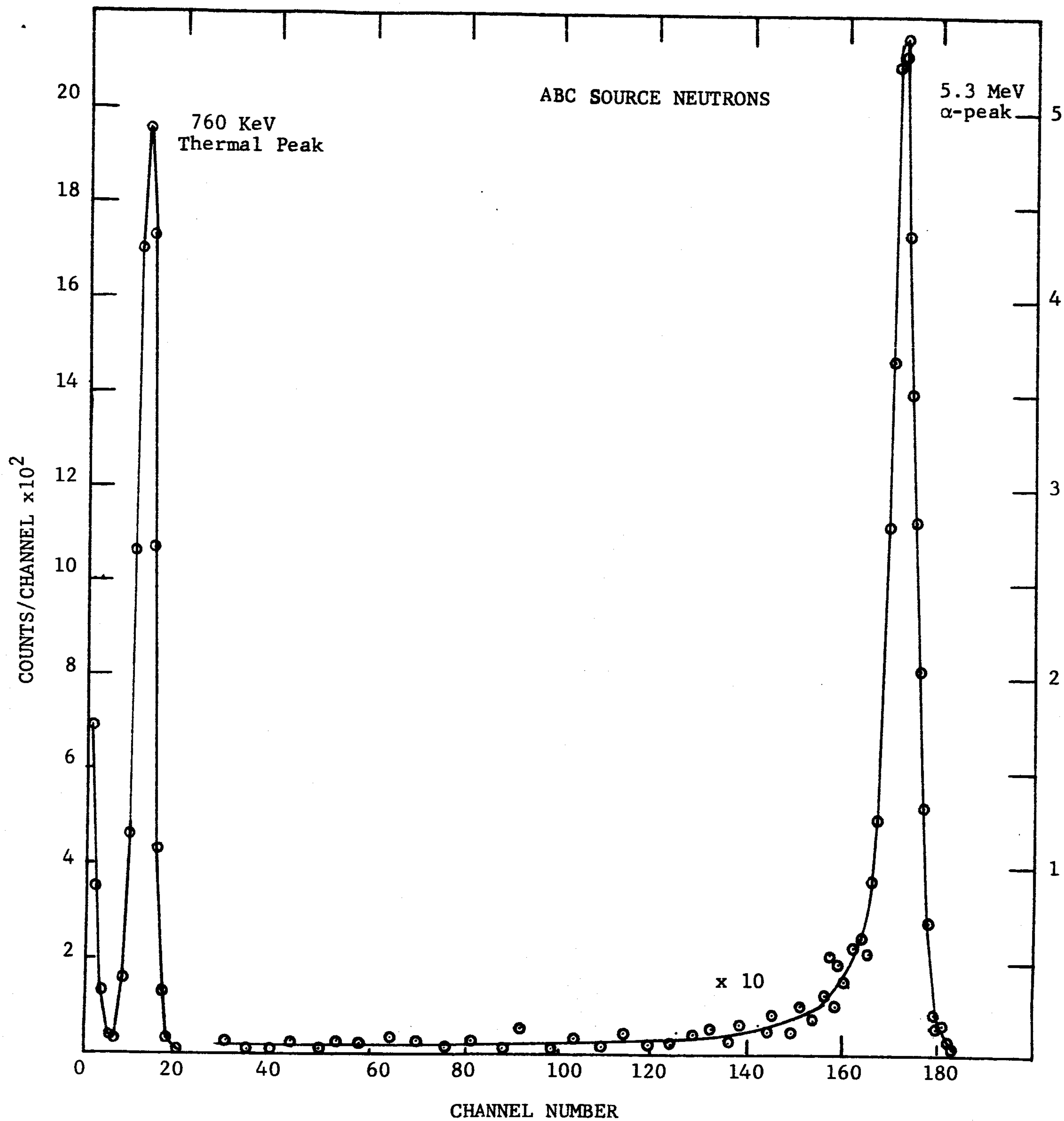

Figure 10

THERMAL PEAK FROM THE ABC SOURCE

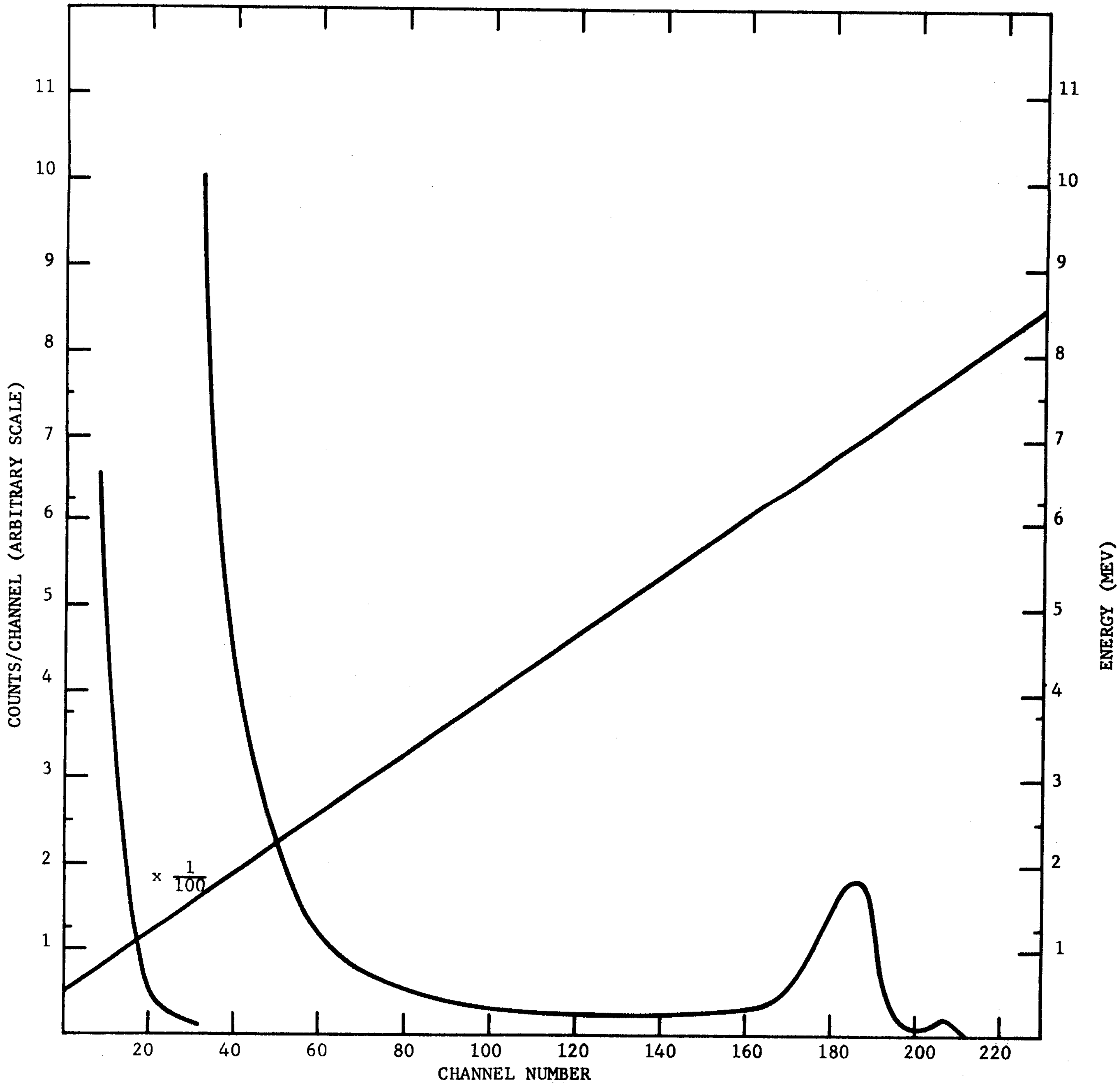

Figure 11
SPECTRUM OF UNSHIELDED ABC SOURCE SPECTRUM

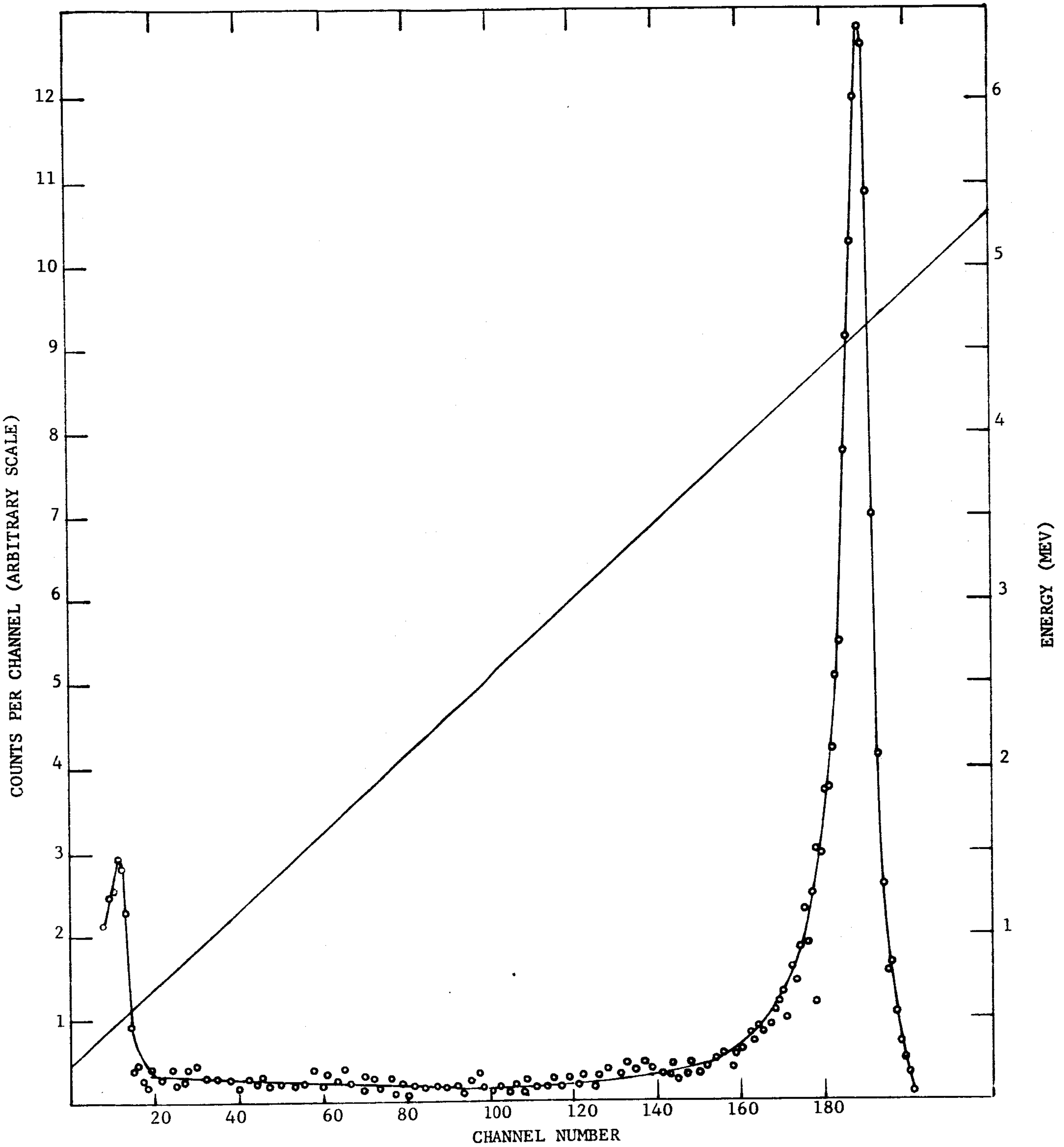

Figure 12

BACKGROUND IN THE SPECTROMETER

counter energy to the solid-state energy was not generally worthwhile because very little energy was actually deposited in the gas. The resolution of the thermal peak was essentially identical to that recorded in the previous experiment. More structure is present in this spectrum, and a small peak occurs at approximately 5.5 MeV. The efficiency was still too small to resolve all the expected peaks from the background.

C. Measurements with Van de Graaff-Produced Neutrons

The IITRI 2-MeV Van de Graaff facility was utilized to generate beams of neutrons from the D-D reaction and the D-T reaction. These results are useful in making a general assessment of the spectrometer operation.

1. D-D Neutron Measurements

The IITRI Van de Graaff generates neutrons up to 5 MeV by using the reaction of deuterons on a titanium target containing adsorbed deuterium. This target is thick compared to the range of a 2-MeV deuteron. Since the number of deuterons having any energy between 0 and 2 MeV is virtually constant, the neutron flux at any angle contains a spectrum of neutron energies resulting from deuterons of all energies up to the maximum. Figure 13 shows a family of curves giving the range of energy of neutrons emitted at a given angle as a function of the initial deuteron energy. From these curves an angle that produces the minimum spread in neutron energy can be selected.

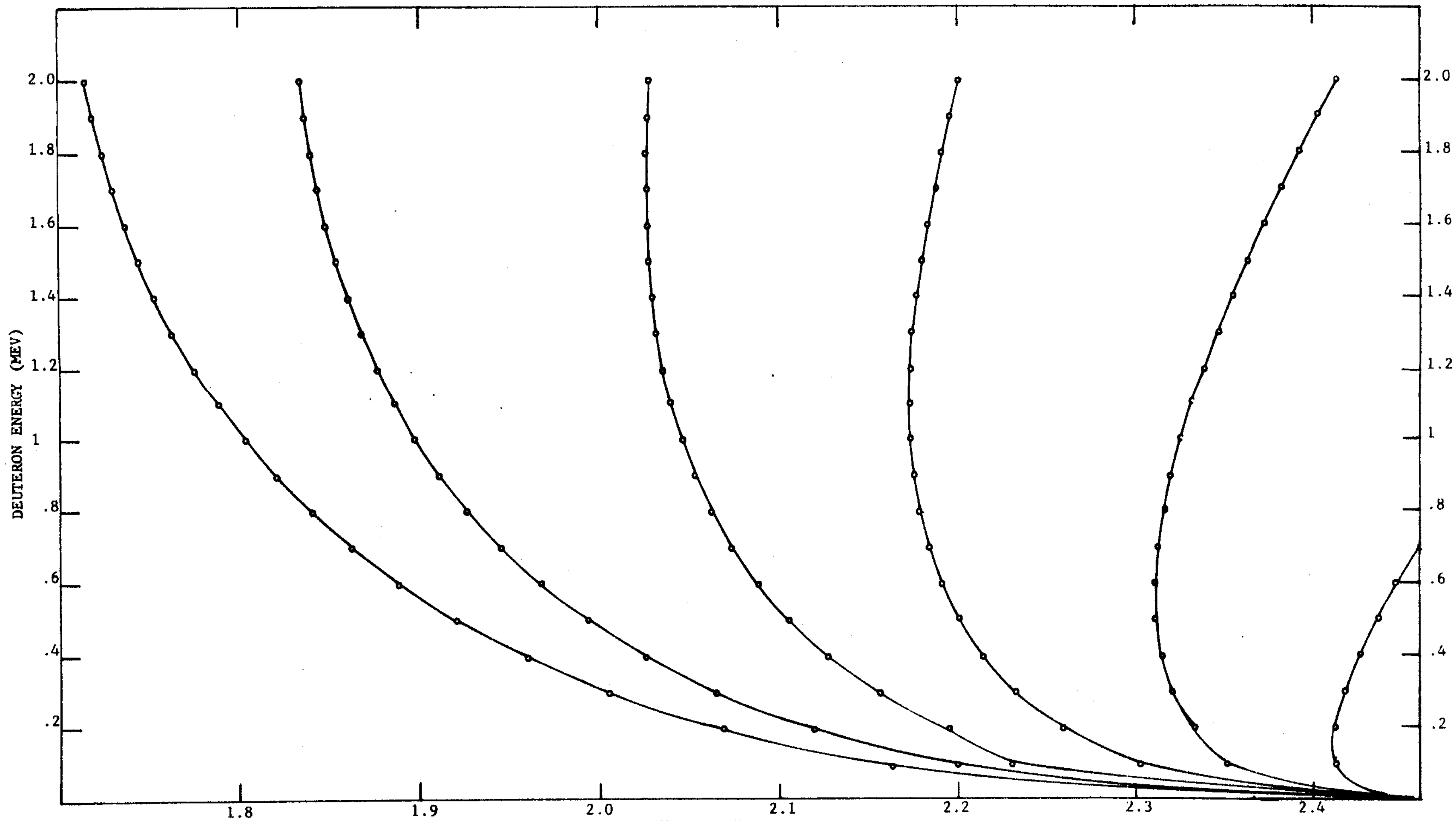

Figure 13

NEUTRON ENERGY A FUNCTION OF DEUTERON ENERGY AT SEVERAL ANGLES

A second factor that influences the energy spread is the angular spread resulting from the non-zero size of the source. A third factor is the non-zero solid angle subtended by the neutron detector. To achieve the minimum energy spread the neutron detector is placed at an angle of 120° with respect to the deuteron beam. At this angle the differential cross section is a minimum, and thus the yield is poor. For angles near either 0° or 180° the yield is greater by a factor of 3. Figure 14 shows a spectrum of neutrons from the D-D reaction for an angle of 140° with respect to the deuteron beam. The deuteron beam energy was 1.5 MeV at a current of 65 microamperes. At this angle the average neutron energy is 2.04 MeV.

The intrinsic full-width at half-maximum energy spread for the neutron beam at 140° is approximately 100 keV. Although the additional spread due to the target size can be neglected, the spread due to the area subtended by the sensitive volume of the neutron spectrometer introduces a further broadening of the energy profile. This broadening could be minimized by moving the detector further away from the target, at the expense of a decrease in beam intensity as well as a rapid increase in the ratio of the scattered to the direct component of the neutron flux. For this spectrum the center of the detector was 4 in. from the target. The angular spread produced by the size of the sensitive volume of the detector was, very approximaterly, an additional 50 keV. Because of the poor statistics of this spectrum, an accurate resolution figure cannot be

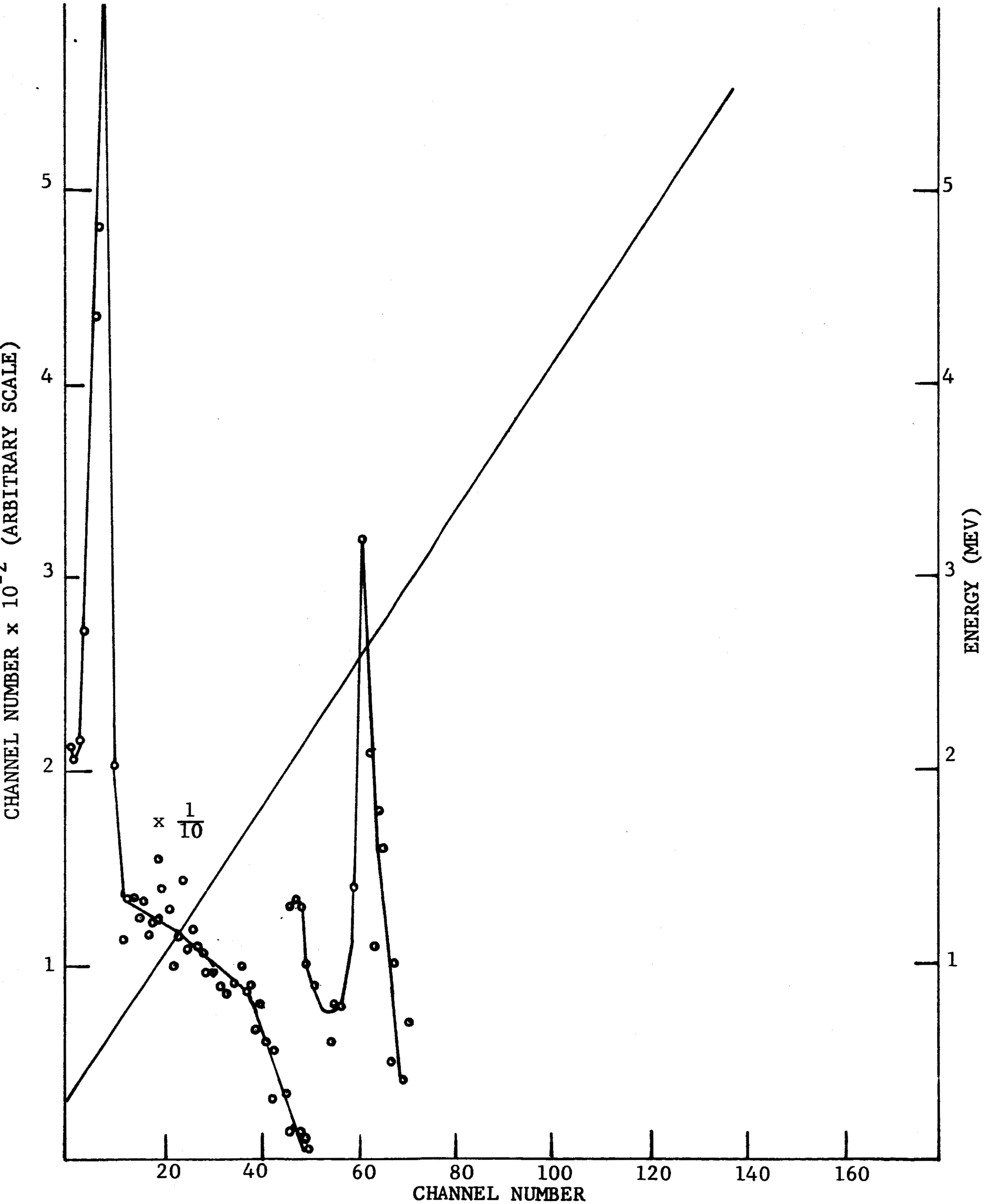

Figure 14

SPECTRUM OF 2.04 MeV NEUTRONS FROM THE D-D REACTION AT 140°

measured, although the width of this peak is certainly not broader than the expected width of 150 keV.

Examination of the thermal peak is also of interest. It can yield some information on the resolution of the detector, especially since the statistics for this peak are 1 percent or better. If the peak were due to thermal neutrons only, it would have a width equal to the resolution of the detector including a contribution due to the loss of energy in the gas. This loss is expected to contribute an additional 75 keV if no addition is performed to account for the loss of energy in the gas of the proportional counters. The measured width in this spectrum is 109 keV. The expected resolution, due to the solid-state detector resolution and the variation of energy lost in the gas, is 100 keV. If the 75-keV variation in the energy loss due to the gas is considered, the resolution is 79^{+12}_{-7}. This figure is in good agreement with the previously determined value.

Figure 15 shows a spectrum taken at 170° with respect to the beam. The half-width of the neutron energy profile at this angle is 230 keV, and the measured half-width of the peak is also 230 keV. The spectrometer was 7 in. from the target. At this distance the energy spread due to the subtended solid angle is small compared with the large intrinsic energy spread.

This spectrum has a peak at 0.9 MeV. The primary neutron energy is 1.76 MeV, and the difference corresponds very closely to the first excited state in Fe^{56} at 0.85 MeV. Since the

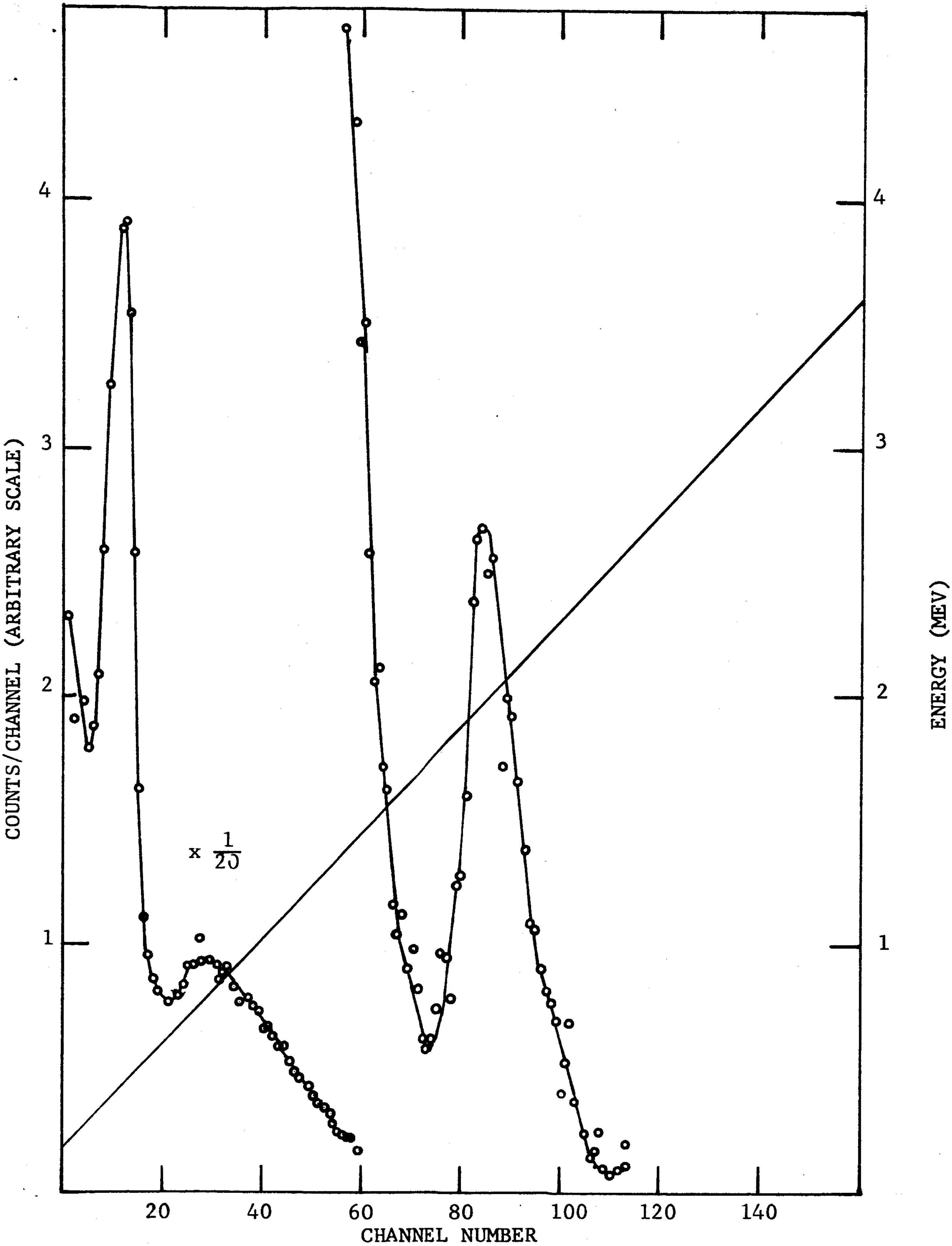

Figure 15
SPECTRUM OF 1.73 MeV NEUTRONS FROM THE D-D REACTION AT 170°

target holder is made of steel, the occurrence of this peak is evidence supporting proper operation of the spectrometer. The cross section leading to this state is not known, so that a relative pulse height cannot be calculated. A peak corresponding to this difference (0.85 MeV) also occurred in spectra taken at 140°, where the neutron energy is 2.0 MeV. This finding indicates that the peak is real and is not a spurious response of the spectrometer.

Figure 16 shows a neutron spectrum again taken at 170°. Although the statistics are better, at 5.3 MeV the poorer detector drifted some 8 channels, which at the neutron energy peak corresponds to 3 channels. This drift worsened the resolution and obscured the peak that should have occurred at 0.9 MeV.

2. D-T 14.8-MeV Neutron Measurements

The cross section of the $He^3(n,p)T$ reaction is approximately 150 millibarns at 14.8 MeV. This is a factor of 5 less than the 2-MeV cross section. Since in the present detector geometry the geometric efficiency is also lower by a factor of 5 at 14 MeV than it is at 2 MeV, the overall detector efficiency will be lower by a factor of 25 at 14 MeV than it is at 2 MeV. Because of this greatly decreased neutron detection efficiency, a neutron dose sufficient to damage the solid-state detector will be accumulated in a time much less than the time required to achieve a precision measurement of resolution and efficiency.

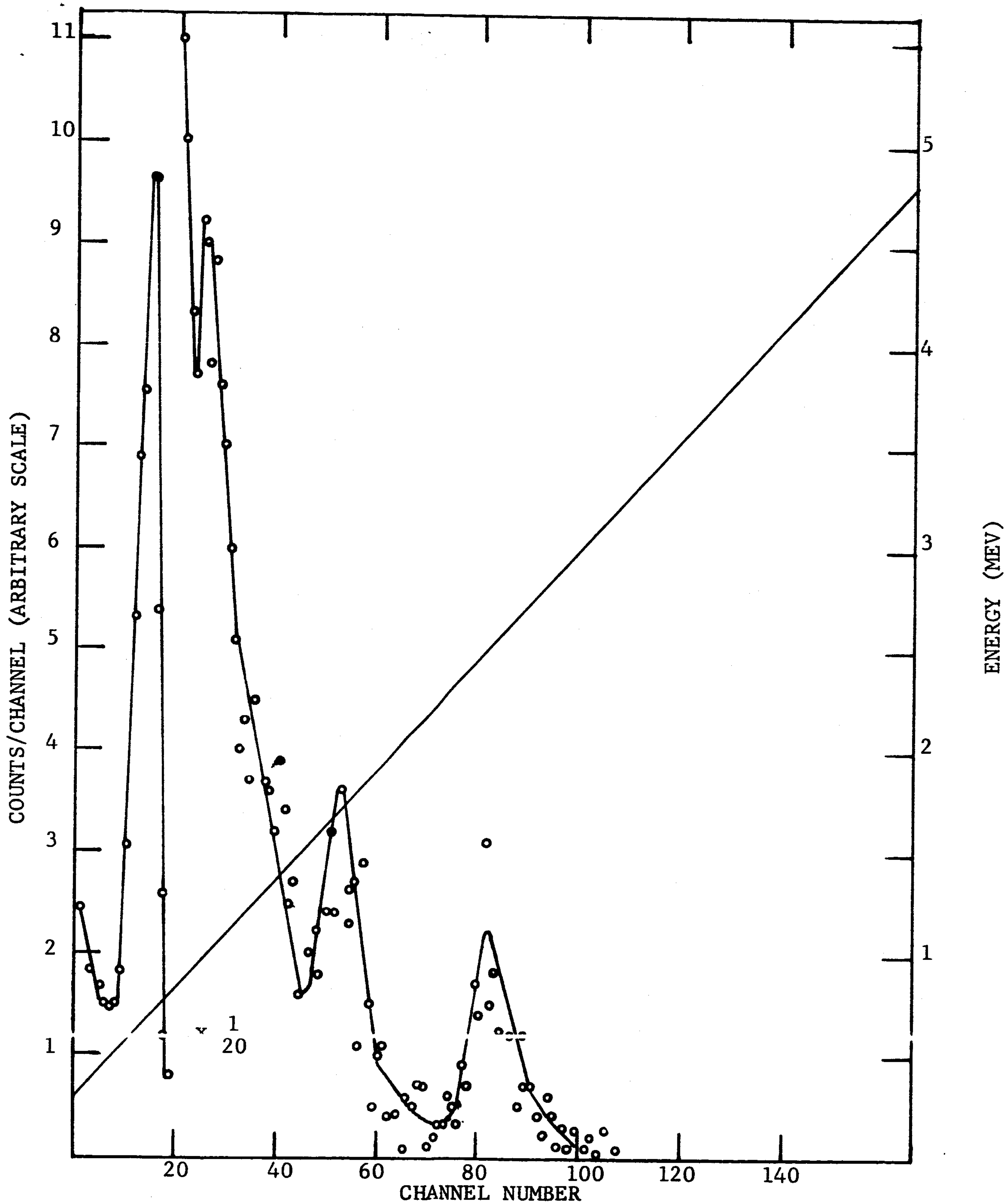

Figure 16

SPECTRUM OF 1.73 MeV NEUTRONS FROM THE D-D REACTION AT 170°

Figure 17 shows a spectrum of the results of a run with 14.8-MeV neutrons. The spectrum extends to 12 MeV, and a small peak occurs at approximately 14 MeV. The resolution of this peak cannot be determined with confidence, although it appears to be no more than 300 keV wide. This value is in agreement with the expected width of the neutron energy spectrum of 250 keV.

D. Response in the Reactor

The spectrometer was operated in the flux from one of the ports in the IITRI 75-kW reactor. Although this port contains no moderator, a large flux of thermal neutrons is present. This flux is reduced by enclosing the spectrometer in a cadmium shield 0.25 in. thick, an amount of material that should have no effect on the fast-neutron spectrum.

A spectrum of reactor fast neutrons is shown in Figure 18. This spectrum was made with the detector filled to 1 atmosphere of 90 percent He^3 and 10 percent C_4H_{10}. The reactor was operating at 100 watts, the neutron flux was 2×10^6/sec above 0.2 MeV based on foil measurements, and the gamma flux was 100 R/hour.

The significant features of this spectrum are the broad peak at 2.0 MeV, extending to 3.5 MeV, and a smaller peak at 1.25 MeV. The presence of the smaller peak was not previously suspected since spectral measurements had been performed with the foil technique exclusively, which yields only broad energy groups. The reality of this peak deserves further investigation.

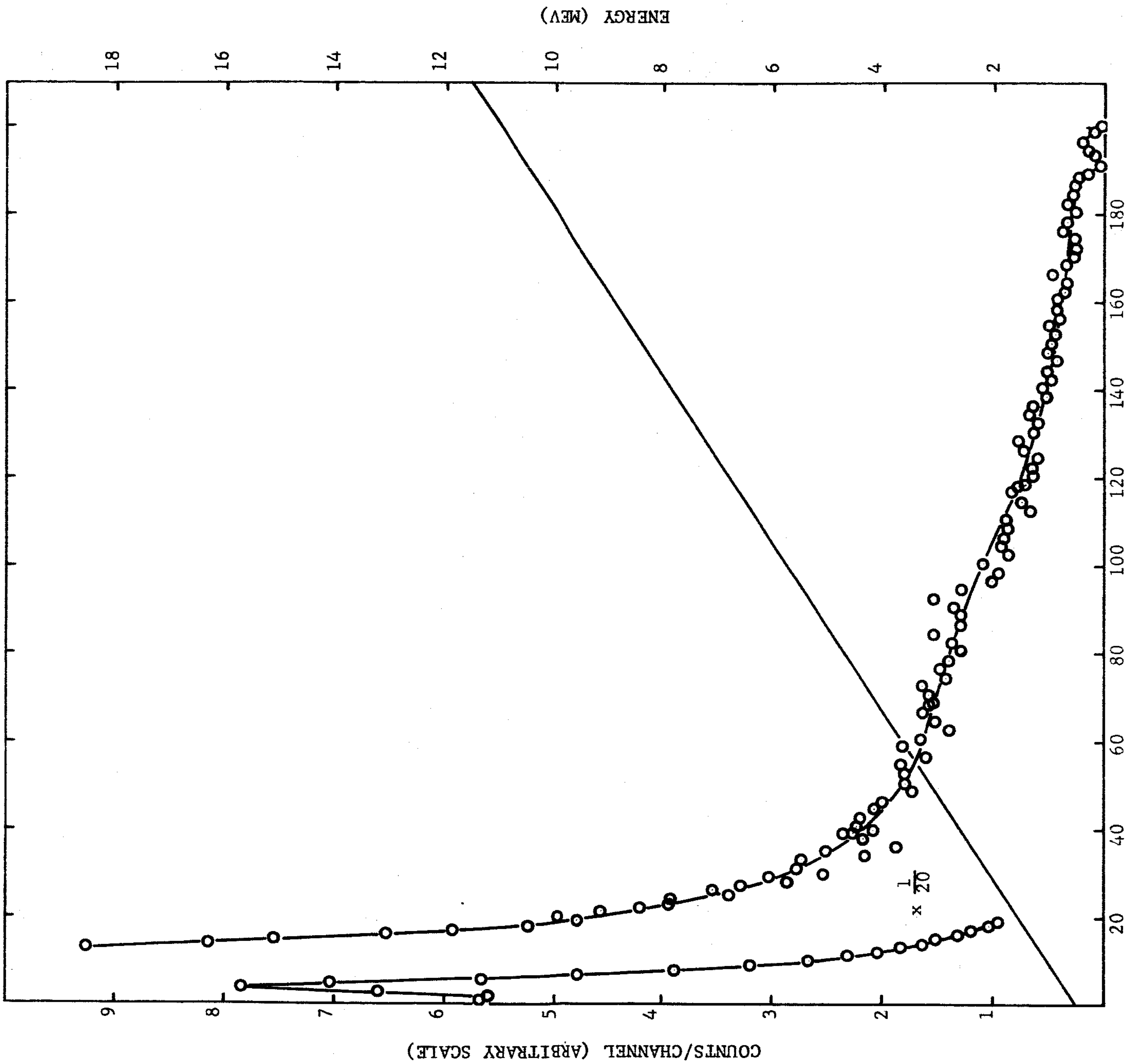

Figure 17
SPECTRUM OF 14 MeV NEUTRON

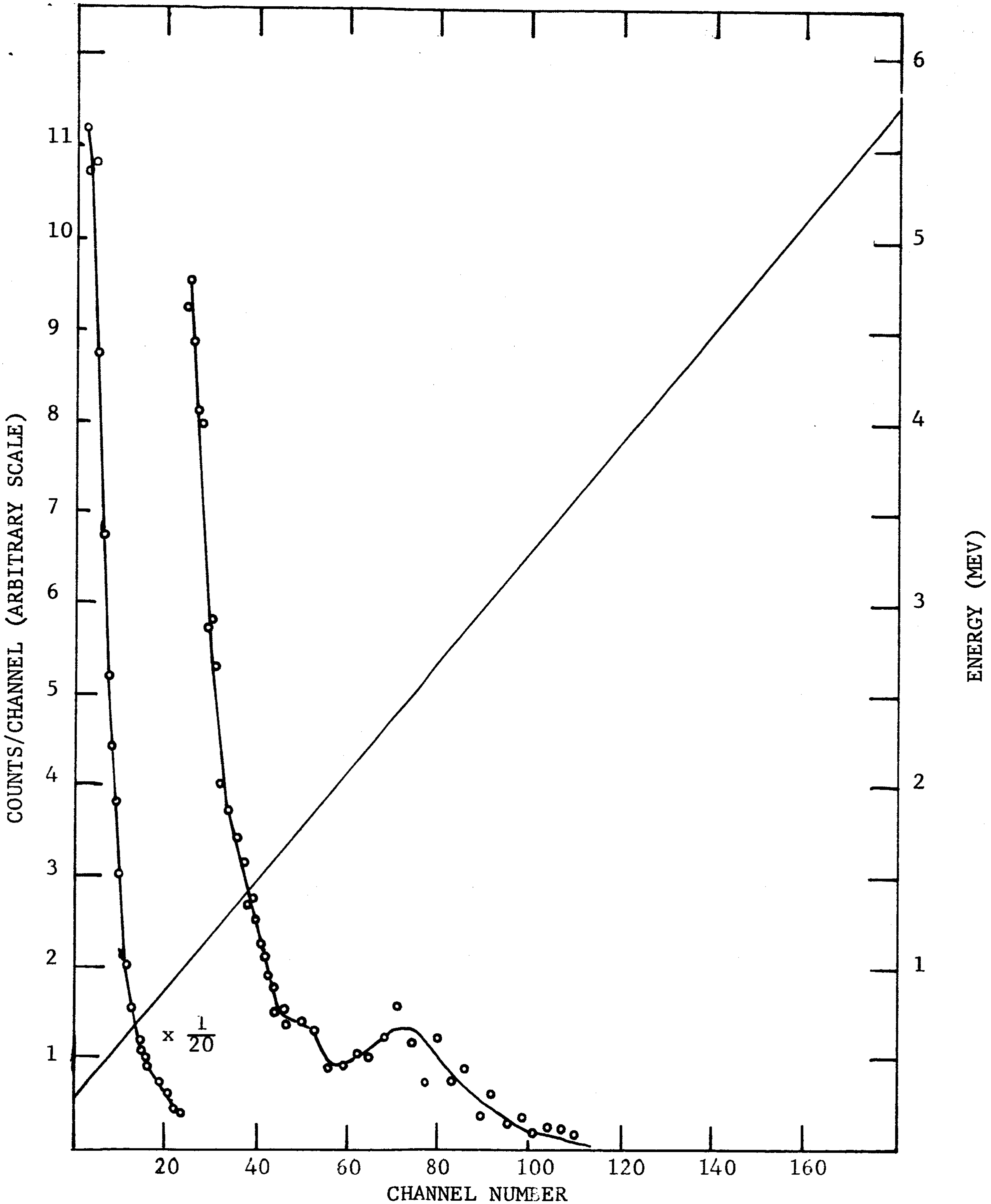

Figure 18

SPECTRUM OF REACTOR FAST NEUTRONS

In the energy region below about 0.5 MeV and extending down to approximately 100 keV, an approximately 1/E neutron spectrum is expected. Since the $He^3(n,p)T$ response is nearly 1/V in this region, the spectrometer response can be calculated on this basis and compared with the measured response. The spectrometer should exhibit a response approximately proportional to $E^{-3/2}$. Measurements on several spectra verified this assumption.

To check the gamma response of the spectrometer, the He^3 gas was replaced with He^4, and several runs were made with and without the cadmium shield. No response above that due to the internal alpha source was observed, even at full reactor power, at which point the gamma field was more than 10^4 R/hour. More detailed information concerning the gamma response is contained in the following section.

From the response of the spectrometer in the approximately known fast-neutron flux from the reactor, fairly detailed information can be derived concerning the average efficiency. Summing the number of counts above 0.2 MeV indicates an efficiency of 2×10^{-6} counts per fast neutron. Since the cross section does not vary rapidly between 0.5 and 4 MeV, this value can be taken as the efficiency throughout this region.

Neutron spectra of the reactor operating at 500 watts and 1 kW were recorded and are essentially identical to that recorded at 100 watts. The coincidence-gate opening circuit associated with the multichannel analyzer was limited to approximately 10^4 counts/min for reliable operation, and thus operation in the reactor flux was limited to levels corresponding to 10^3 watts, since at 10^3 watts the large thermal neutron cross section in the $He^3(n,p)T$ reaction produced 10^4 counts/min even with the cadmium shield.

These reactor spectra illustrate a difficulty inherent in the measurement of a spectrum in which the number of neutrons as a function of energy varies by several orders of magnitude. In such a situation, as is generally the case in reactors, it may be impossible to measure the complete spectrum with a single detector in a reasonable time, even though the detector responds uniformly over the full energy range. Count rate restrictions imposed by the high flux region may severely limit the quantity of data recorded when the flux is low. The use of two detectors frequently overcomes this problem since each detector can be operated over a limited energy range.

E. Response in Intense Gamma Fields

As mentioned in the previous section, the gamma response was extremely good up to levels of approximately 10^3 R/hour. How it responds to higher levels is quite important because the contemplated environment will involve fields as high as 1.5×10^6 R/hour.

In a gamma field of 10^3 R/hour, calculated at 95 cm from a 700-curie Co^{60} source in the IITRI hot cell, the response of the proportional counters at 0.25 atmosphere of 90 percent He^3 and 10 percent C_4H_{10} was negligible. The solid-state detectors, on the other hand, exhibited a counting rate of 10^3 counts/min above 0.1 MeV. Most of this response was below 0.5 MeV. This count rate is tolerable and would have no measurable effect on the neutron spectrum, since the proportional counter coincidence eliminates any counts resulting from gamma interaction only and the number of chance coincidences between neutron and gamma events is very small.

In a gamma field of 10^4 R/hour, the response of the proportional counters increased to 25 ± 5 counts/min. The solid-state detectors recorded more than 10^4 counts/min, but again this rate is well below that which would cause serious pileup due to accidental coincidences.

In a gamma field of 10^5 R/hour, the coincidences in the proportional counters amounted to 300/min at 25-nanosec resolving time. This is still quite low compared with the neutron response that would be recorded in a neutron flux of $10^8/cm^2$-sec at an efficiency of 10^{-6}/neutron. However, in this field gamma pileup in the solid-state detectors is a serious problem. It is doubtful that a reliable neutron spectrum could be recorded since most of the response would be due to accidental summing of gamma and neutron events in the solid-state detector channels. The count rate recorded in each detector channel exceeded 10^5 counts/min, and amplifier saturation was apparent during a significant portion of the time. This is caused principally by the preamplifiers, whose time response is much slower than that of the main amplifier.

In the highest gamma field employed, 10^6 R/hour, the proportional counters produced 5×10^3 counts/min at 25-nanosec resolving time. This rate still represents very good gamma insensitivity, especially since it is realized that for random coincidences the rate should be proportional to the square of the field rather than directly proportional, as has been shown. This indicates that these coincidences are due to some mechanism that deposits energy in both proportional counters from one gamma interaction. The solid-state detector channels were completely saturated under these conditions, and no count rate information could be obtained. However, it is clear that a rate of the order of 10^6/min is to be expected. The preamplifiers were virtually continuously blocked. Because the count rates in the solid-state detectors were so high, use of particle identification to further reduce the gamma background count rate could not be attempted, although such a reduction is possible and can amount to as much as two orders of magnitude. This was also true in the case of the measurements at 10^5 R/hour. At the lower fields a reduction of 10 is easily achieved, so that in a field of 10^4 R/hour the measured 25 counts/min could be reduced to such a level that it was masked by statistics.

V. RESULTS

A. Resolution

The present prototype has an ultimate resolution of 54 keV. Based on measurements of the thermal neutrons, the resolution is

100 keV or better. The discrepancy can be accounted for by considering the variation in energy loss of the proton and triton in the gas and the substantial number of 50-keV neutrons contributing to the thermal peak.

At higher neutron energies, where the energy deposited in the gas is much smaller, the resolution should improve. This has been observed at 1.73 MeV, but the precise amount of this improvement is difficult to quantify because of the poor statistics involved.

At the highest energy, 14.2 MeV, the greatly lowered efficiency makes measurement of resolution more difficult still. However, on the basis of the present results we can estimate that a peak resolution of 300 keV is being achieved. This resolution is to be compared with the half-width of the neutron energy profile, which is no less than 250 keV in a thick target. The result is consistent with the thermal neutron measurements which indicate a resolution of 100 keV or better.

If the variation in energy lost in the gas for the proton and triton produced by a thermal neutron is considered, a resolution figure that should hold reasonably well for higher neutron energies can be calculated. The results are not inconsistent with a resolution of 75^{+15}_{-10} keV. On the energy scale, this represents a resolution of 8.7 percent for a 100-keV neutron. This figure should be compared with the resolution requirement of 8 percent resolution at 100 keV as stated in Request No. 1-5-41-50634. We confidently expect to be able to improve this figure substantially.

B. Efficiency

The efficiency of the spectrometer can be calculated with some confidence by considering the cross section of the $He^3(n,p)T$ reaction, the He^3 gas pressure, and the geometry of the detector. At a gas pressure of 1.0 atmosphere, neutron energies of 0.3 to 3 MeV (where the $He^3(n,p)T$ cross section is nearly constant), and the present geometry, the efficiency was calculated to be 3.2×10^{-6}/neutron. The efficiency at approximately these energies, based on measurements taken at 0.25 atmosphere, was 2.0×10^{-6} and reflects the approximate nature of the calculation of the geometric effect on efficiency. There is no reason to believe that the efficiency should not be proportional to pressure, and a measurement made at 1.0 atmosphere but with poorer statistics corroborated this view. At the highest reasonable gas pressure, 2.0 atmospheres, the efficiency will be 4×10^{-6}/neutron. A geometry change that places the two solid-state detectors closer together is expected to improve this efficiency by a factor of 10.

C. Gamma Rejection

Although the gamma interaction in the gas and consequently the coincidence rate due to gamma interaction are as low as expected, the interaction of gammas in the solid-state detectors represents a serious problem because of pileup in the preamplifiers.

An approximate calculation of the gamma interaction in the gas indicated that the observed gamma-produced coincidence rate arose principally from electrons ejected from the solid material enclosing the gas, that is, the walls and solid-state detectors and their mounting. Use of either a simple triple coincidence or the more efficient particle identification reduced this background to much lower levels.

At 10^3 R/hour, no gamma interaction is expected to be observable, and this was verified by experiment. At higher levels it is not possible in general to calculate the expected background coincidence rate, but the experimental results at 10^4 R/hour and 10^5 R/hour make it clear that operation in fields of this magnitude will not involve any inherent difficulties. Operation in fields of 10^6 R/hour requires some special technique to overcome the serious problems of pileup.

D. Count Rate Capability

During operation in neutron fluxes up to 10^8/sec, count rates as high as 2×10^3/sec can be accepted by each of the four channels without distortion. The limitation in count rate occurred in the gate circuit used to open the multichannel analyzer and is not inherent to the system. This gate was limited to 200 counts/sec for a constant pulse width. Relatively minor changes in this circuit will allow analysis of information at the rate of 1000/sec, the limit of the present multichannel analyzer. A fast analyzer would allow analysis of information at a rate at least as great as 2×10^3/sec.

E. Summary

In Table I the major parameters desired of the spectrometer are compared with the measured parameters of the prototype and with the results expected ultimately.

VI. RECOMMENDATIONS

Further work on several items in the present spectrometer may lead to improved characteristics of the spectrometer or to greater confidence in basic understanding of its operation. These items are discussed in the following sections.

A. Spectrometer Improvements

Increased efficiency will be possible with an improved geometry, and at the same time better proportional counter response will be achieved. The latter may have a significant effect on detector resolution, especially at low neutron energy.

A method that further reduces the gamma background and eliminates the problem of pileup in the solid-state detector preamplifiers is a matter of some importance. A method of achieving this end is the use of fast amplifiers feeding a linear gate (ref. 27) that is only opened in response to a signal from the proportional counter coincidence circuit. With this arrangement the pulse rate due to gamma background in the preamplifiers and the amplifiers can be limited to that of the proportional counters, which is well within the tolerable limit of approximately 500 counts/min for an efficiency of 10^{-5} counts/neutron in a flux of $10^{8}/cm^{2}$-sec.

Table I

COMPARISON OF DESIRED CHARACTERISTICS, PROTOTYPE CHARACTERISTICS, AND ULTIMATELY ACHIEVABLE CHARACTERISTICS

	Desired Characteristics	Prototype Characteristics	Achievable Characteristics
Energy range	0.1-14 MeV	0.1-14 MeV	0.1-14 MeV
Resolution	69 keV	$75\ ^{+15}_{-10}$ keV	30 keV
Efficiency	10^{-5}	2×10^{-6}	2×10^{-5}
Gamma rejection (neutron/gamma ratio for 10% background)	$\frac{10^2 \text{ neutrons/cm}^2\text{-sec}}{\text{R/hr}}$ in fields of 1.5×10^6 R/hr	$\frac{10^2 \text{ neutrons/cm}^2\text{-sec}}{\text{R/hr}}$ limited to fields of 10^4 R/hr	$\frac{10^2 \text{ neutrons/cm-sec}}{\text{R/hr}}$ in fields of 1.5×10^6 R/hr
Response time	2×10^3 pulses/sec	$>10^3$ pulses/sec	5×10^3 pulses/sec

This system will allow fast-neutron spectra to be measured in the presence of very large gamma fluxes as high as 1.5×10^6 R/hour without the use of any gamma shielding.

B. Thermal Neutron Count Rate Reduction

As noted earlier, a large thermal neutron flux severely limits the ability to record large fluxes of fast neutrons. To reduce this limitation, a thermal shield should be fabricated. This shield will greatly reduce the flux of neutrons below some energy, for example, 1 keV, but will have a negligible effect at higher energies. A boron shield enclosing the detector unit fulfills this requirement yet increases the dimensions of the detector unit only negligibly.

C. Advanced Confidence Testing

A number of tests on the improved system and on the present system will further understanding of the spectrometer's basic operation and capabilities and will develop confidence in its use. Such advanced testing should include tests in mixed neutron and gamma fields up to at least 10^{10}/cm^2-sec and 1.5×10^6 R/hour, respectively. Additionally, tests can be performed with highly monoenergetic neutron bemas in the range of 0.5 to 1.5 MeV. The full-width at half-maximum of these beams can be as low as 10 keV, which will allow precise determination of the resolution.

Such tests will provide information on resolution efficiency and gamma rejection under a variety of conditions and will yield evidence on the degree of confidence that can be placed in the system.

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